HOW TO MAKE GOOD CONCRETE

BY

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PREFACE

It is easy to make good concrete where good aggregates are supplied by merchants of repute. It is easier to buy ready-mixed concrete—if the job is within reach of a ready-mixed concrete factory. However, most engineers, architects, contractors, builders, and manufacturers of concrete products, cannot rely on these facilities. They have to decide which are the best of available aggregates, which may be used or must not be used, and, often, how to make the best possible use of aggregates that are known to be far from good but must be used.

This book is written principally for those who have to make such decisions. Those who work among the facilities referred to above, and those who have to produce concrete on a large scale while supplying their own aggregates, are referred especially to Chapters VII to XV.

The author is indebted to the Institution of Civil Engineers of Ireland for permission to reproduce *Figs.* 13 to 22 from a paper dealing with his own research work published in Vol. LXII of the Transactions of the Institution. He is also indebted to H.M. Stationery Office for permission to reproduce *Fig.* 28, and to the British Standards Institution for permission to reproduce certain standards in Appendixes 1 to 5 inclusive. The test methods described in Appendixes 6 and 7 are from the Recommendations for a Code of Practice for the use of Reinforced Concrete in Buildings.

H. N. W.

February, 1939.

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Again, with one sand 1 : 2 : 4 concrete is quite easily workable ; with another it is harsh. Sometimes even with the same sand concrete is more workable on some days than others.

Variations in Amount of Cement.—Again, suppose that, having been accustomed to measuring cement by loose volume, he takes a contract with an architect or engineer who specifies bag batches. He finds that his costs go up mysteriously. Measurements show that 1 : 2 : 4 concrete now contains 510 lb. of cement per cubic yard instead of about 450 lb., to which he has been accustomed. Investigation shows that in fixing the proportions per bag batch he assumed cement to weigh 90 lb. per cubic foot, whereas his cubic foot of loose cement weighed only 80 lb. Thus the proportions by volume in both cases are 1 : 2 : 4, but the bag-batch method needs 90 lb. of cement with 2 cu. ft. of sand and 4 cu. ft. of coarse aggregate whereas the loose-volume method requires only 80 lb. of cement with the same volumes of aggregate. As the yield of hardened concrete depends largely on the volume of aggregate used, and these are the same in both cases, it is clear that a given volume of hardened concrete requires more cement in the bag-batch method.

Formerly his so-called 1 : 2 : 4 mix was really 1 : $2\frac{1}{4}$: $4\frac{1}{2}$. Now when he makes a real 1 : 2 : 4 concrete based on 1 cu. ft. of cement weighing 90 lb. he finds that the increase in cement involves an extra cost of about 1*s*. 3*d*. per cubic yard of concrete. If, at the same time, the coarse aggregate is a crushed stone containing some elongated and flat particles the cement content tends towards 520 lb. per cubic yard ; this happens because the crushed stone packs badly in the measuring box, a smaller absolute volume of stone particles is used, and the concrete is therefore richer in cement. Suppose that in another case a contractor is using a single aggregate, a gravel containing sufficient sand to make workable concrete when used as it comes from the pit. He is mixing $7\frac{1}{2}$ cu. ft. of this with one bag of cement. He finds that in very wet weather he gets 25 cu. ft. of concrete for every 27 cu. ft. of gravel, and in dry weather he gets only $23\frac{1}{2}$ cu. ft. of concrete for 27 cu. ft. of aggregate. Or, looking at it from the point of view of yield of concrete per bag of cement, he finds that in the wet weather he gets 7 cu. ft. of concrete per bag of cement and in dry weather only $6\frac{1}{2}$ cu. ft. of concrete per bag of cement. What is the explanation ?

The Solution.

How are these difficulties to be avoided ? How is uniformly good concrete to be made with varying materials ? These questions constitute a problem with which many contractors are faced.

The solution is not difficult, assuming the use of clean and sound aggregates. First of all care must be taken to ensure that the intended proportions of the materials are actually used.

Proportions of Cement.

> *The only safe way of measuring cement is by weight, either by actual weighing or by using the 112-lb. bag as the basis of each batch.*

Normally cement is assumed to weigh 90 lb. per cubic foot. By loose volume a finely-ground cement may weigh only 75 lb. per cubic foot.

Proportions of Sand.

Sand is generally measured by volume, especially on small works.

> *The quality and volume of the finished concrete depend largely, other things being equal, on the weight of* dry *sand particles used.*

This weight is proportional to the volume *only while the sand is dry* and the same method of filling the container is used. Even when the method of filling is exactly the same, the weight of actual sand particles in one cubic foot varies considerably with the amount of moisture in the sand.

Bulking of Sand.—Fill a cubic foot measure with fine sand that is perfectly dry. Throw out the sand and mix 5 per cent. by weight of water with it. On refilling the measure it will be found that all the sand will not fit into it. There is about one-third of a cubic foot left over. The total volume is about $1\frac{1}{3}$ cu. ft. That is, the cubic foot measure can now contain only about three-quarters of the weight of actual sand particles that it contained when the sand was dry. The weight per cubic foot is reduced from about 100 lb. to about 75 lb. Take the damp sand out of the measure. Put about one-third of a cubic foot of water into the measure. Now put back the sand, adding water, if necessary, so as to keep the water surface just above the top of the sand. It will be found that all the sand can be put back into the measure again.

> *Whether dry or saturated, sand occupies the same volume. In any intermediate stage the volume is increased. This is the phenomenon known as bulking.*

Consequences of Bulking.—Now suppose that proportions and quantities have been based on the use of dry sand. Suppose the contractor uses this sand when it contains about 5 per cent. or 6 per cent. of water. He is then using only three-quarters of the required amount of sand, and the mix is richer. That is, he thinks he is using, say, a 1 : 2 : 4 mix, whereas he is actually using a 1 : $1\frac{1}{2}$: 4 mix.

The extent of the bulking depends on the fineness of the sand. An extremely fine " rabbit " sand may bulk as much as 40 per cent. with about 10 per cent. of water, while a very coarse sand will show a maximum increase in volume of only about 10 per cent. with about 4 per cent. of water. Sands ordinarily used lie between these limits and bulk about 20 per cent. to 30 per cent. with 5 per cent. to 7 per cent. of water.

The Cure for Bulking.—One way of avoiding the effects of bulking is to saturate each batch of sand in the measuring box, because saturated sand has the same volume as dry sand, and it is easier and cheaper to inundate sand with water than to dry it. However, a simple apparatus now available enables an allowance for the effect of bulking to be made easily. A measurement, requiring no special skill, shows the percentage of sand which should be added to the specified volume to compensate for the effect of bulking. The measurement can be made in a few minutes, and the calculation of the increased volume of sand is of the simplest nature. One or other of these precautions is necessary to ensure a constant proportion of sand.

Coarse Aggregate.

The volume of coarse aggregate is not affected by water content unless it contains some sand. Even then the extent of the bulking is small. Sometimes, however, pit gravels containing 40 per cent. to 50 per cent. of sand are used ; in such cases an allowance for bulking may be necessary, especially if a high proportion of fine sand is present.

Effect of Bulking on Yield of Concrete.—The different yields of concrete got with a " run-of-pit " gravel in wet and dry weather are due to bulking of the sand. In very wet weather the gravel is almost saturated and its volume is nearly the same as if it were dry. In dry weather the gravel is not dry, but just moist enough to have its volume increased by the effect of bulking of the sand in it. Consequently 27 cu. ft. of gravel contain a greater weight of solid particles in wet weather than in fine ; and a bigger yield of concrete results in wet weather.

Effect of Sand on Workability.—The workability of concrete of the same proportions depends largely on the grading of the sand.

> *For the same proportions and the same coarse aggregate, fine sand makes the concrete workable, but coarse sand tends to make it harsh.*

Thus a 1 : 2 : 4 concrete made with a fine sand may be easily workable, whereas if made with coarse sand it may be harsh. If there is no alternative to the coarse sand, the proportions of the mix must be changed. The proportion of sand should be increased, and the proportion of coarse aggregate slightly decreased.

In districts in which all available sands are somewhat coarse it is impossible to make workable 1 : 2 : 4 concrete with crushed stone of $\frac{3}{4}$-in. maximum size, and even 1 : $1\frac{1}{2}$: 3 concrete may be too harsh for some purposes, especially if no allowance is made for bulking effects.

On this account it is not wise for engineers and architects to specify too rigidly the relative proportions of fine and coarse aggregates. It is often unfair to contractors to enforce rigid specifications of relative proportions of fine and coarse aggregate when the only available fine aggregates are too coarse. It is better to specify the cement content of the finished concrete and to allow some latitude in the actual proportions of the mix by specifying that the proportions, while nominally, say 1 : 2 : 4, shall not be finally fixed until the aggregates proposed for use have been tested.

Detailed guidance as to the gradings of sand that are suitable for mixes of different proportions will be given later.

Proportions of Cement to Aggregate.

> *While the proportions of cement to sand and to coarse aggregate must be known, it is not these proportions that are most important, but the proportion of cement to combined aggregate, that is of cement to the volume occupied by the fine and coarse aggregate when mixed together.*

In a nominal 1 : 2 : 4 concrete the equivalent proportions of cement to combined aggregate by loose volume are 1 to 4·9, or roughly 1 to 5. This proportion and the

grading of the combined aggregate are most important. The use of 1 : 2 : 4, or other mixes containing twice as much gravel as sand, assumes that the volume of sand should be half that of the coarse aggregate. It is neither necessary nor satisfactory to maintain this proportion between fine and coarse aggregate, and variations should be allowed provided the proportion of cement to combined aggregate is not changed; or more strictly, provided the cement content of the finished concrete is not seriously altered.

The volume of mortar should be sufficient to fill the voids in the coarse aggregate and make the concrete plastic. The proportion of sand depends on the amount of cement in the mortar. The richer the mortar is in cement the less sand is necessary in proportion to the coarse aggregate. It is true that under certain conditions, and especially with sands that are somewhat fine, proportions in which the volume of coarse aggregate is twice that of the sand are excellent within limits. But the requisite conditions are frequently absent, and adherence to these proportions then leads to trouble. It is therefore better to specify either the cement content of the finished concrete or the proportion of cement to combined aggregates, especially when nothing is known beforehand of the aggregates likely to be used. Better concrete can be made in accordance with such a specification in many districts in which the available sands are not suitable for proportioning in such ratios as 1 : $1\frac{1}{2}$: 3, 1 : 2 : 4, 1 : $2\frac{1}{2}$: 5, etc.

Proportion of Water to Cement.

The general quality of concrete, especially its strength, depends on the proportion of water to cement in the mix.

A certain minimum proportion of water is necessary in order to hydrate the cement completely. More water than this is necessary to make the concrete sufficiently workable to be placed by ordinary methods. So long as the concrete is sufficiently workable to be compacted by the method of placing used, its strength depends on the proportion of water to cement in the mix; the greater the proportion of water the weaker the concrete. Density and impermeability (and therefore durability) and subsequent shrinkage are also adversely affected by excess water. It is therefore most important to control the proportion of water. This should not be allowed to exceed specified limits for various classes of concrete, and, in general, should be kept as low as the methods of placing will allow.

Grading of Combined Aggregate.

Once the proportion of cement to combined aggregate and the limiting proportion of water to cement are fixed, the grading of the combined aggregate becomes the most important factor affecting the quality of the concrete.

Provided the grading of the combined aggregate lies within certain limits the concrete will be excellent. With gradings outside these limits the quality may fall off rapidly according to the way in which the grading differs from that which is most suitable for making good—that is, workable, dense, and relatively strong—concrete. Details of gradings of combined aggregates that are suitable for making

good concrete will be given later (p. 47). From these, gradings for separate fine and coarse aggregates may be deduced.

Gradings for Separate Fine and Coarse Aggregates.

SAND.—It is commonly required that sand should all pass a $\frac{3}{16}$-in. sieve, and for ordinary purposes that not more than 5 per cent. should pass a No. 100 British Standard sieve. Between these limits the sand ought to be reasonably uniformly graded. More details of sand gradings will be given later (p. 64).

COARSE AGGREGATE OF $\frac{3}{4}$-IN. MAXIMUM SIZE.—All or nearly all of this should pass a $\frac{3}{4}$-in. sieve and be retained on a $\frac{3}{16}$-in. sieve. From about 67 per cent. to 50 per cent. should pass a $\frac{3}{4}$-in. sieve and be retained on a $\frac{3}{8}$-in. sieve, the former for richer mixes and the latter for lean. Gradings for other maximum sizes will be given later.

On small jobs it is seldom economical to screen the sand and gravel, and a sand containing pebbles greater than $\frac{3}{16}$-in. may have to be combined with a gravel or crushed stone containing particles smaller than $\frac{3}{16}$-in. As will be shown later, it is frequently possible to make good concrete with such materials. The proportion in which the fine and coarse aggregates should be combined depends on the manner in which each is graded.

While the apparatus necessary for determining the gradings of aggregates is simple and not very expensive, and the procedure in determining the proper proportions of aggregates is not difficult, both may be beyond the resources of some contractors. The necessary testing and determination of proportions can then be entrusted to a testing laboratory. The cost of the testing will be more than repaid to the owner in the quality of the work, and frequently much more than repaid to the contractor by a saving in cement.

Placing.

Concrete should be placed by methods that ensure thorough compacting—rodding, spading, tamping, or vibrating according to the nature of the work. In every case care should be taken to ensure satisfactory placing in shuttering that is rigid and watertight.

Maturing.

The concrete, when placed, should be kept moist for at least seven days and preferably for fourteen days.

Very early drying out is bad practice. (In this connection it is important to note that timber shuttering should be either oiled or drenched with water immediately before concrete is placed to prevent it from absorbing water from the concrete.) Cubes or blocks taken from the moulds on the day after casting and left lying in the open in fine weather attain only about two-thirds of the strength at seven days of cubes of the same mix cured in water for seven days. The strength and impermeability of concrete products are often seriously impaired by too rapid drying, especially those which are cast with very dry concrete and immediately taken from the moulds. The author has seen concrete pipes in which nearly $\frac{1}{8}$ in. thickness both inside and outside was not really concrete at all, because bad maturing conditions allowed it to dry too quickly.

Solution Summarised.

Assuming the use of good cement and that the water and aggregates are clean, the solution of the problem of making uniformly good concrete entails the following:

(1) Weighing the cement or using the 112-lb. bag as the unit and avoiding loose volume measurements.
(2) Making allowance for the bulking of the sand.
(3) Securing the correct proportion of combined aggregate to cement.
(4) Ensuring that the grading of the combined aggregate is within certain limits.
(5) Keeping the proportion of water to cement below specified limits.
(6) Thorough mixing.
(7) Careful placing and compacting.
(8) Adequate maturing in moist conditions.

Details of methods will be given later.

CHAPTER II

GENERAL CONSIDERATIONS

Latitude Allowable.

In considering the many variables and possibilities of wrong combinations suggested in the last section, one might be led to the conclusion that it is difficult to make good concrete. Actually, however, considerable latitude is allowable in the proportions of the materials and the nature of the aggregates, and this latitude is somewhat increased by the high quality of modern cements. Consequently, it is relatively easy to make good concrete provided the aggregates are reasonably good. Just as with modern high-class photographic films there is so much latitude in exposure that it is possible to make good photographs with a wide range of exposures and times of development, so it is easy to make good concrete despite variations in the materials. But to make a series of negatives all of the same density and degree of contrast requires carefully timed exposures and development, and is not at all so easy as making photographs that are merely good. So also to make good concrete of a predetermined quality and to produce that quality consistently is not at all easy. The quality of each material must be good ; the proportions must be correct ; and the stages of mixing, transporting, placing in the shuttering, and maturing must be carefully controlled and incessantly watched.

Not only must good materials be chosen, but their quality must be maintained while, perhaps, hundreds of cubic yards of concrete are being manufactured. In making concrete we decide on the kind of cement to be used, whether normal, rapid-hardening, or special. We know that its manufacture is controlled so that it may conform to carefully specified standards, and we ensure its quality by testing samples from every consignment. The water is usually of suitable quality ; otherwise we ascertain by chemical analysis that it is sufficiently pure. Then we dig the aggregates out of the ground, dredge them from a lake or river, provide them by crushing stone, or we buy them from a pit owner who may or may not have been careful in their preparation ; and we often accept them as they come.

Importance of Aggregates.

We specify that the aggregates shall be clean, sound, and strong, free from deleterious materials, and well graded. We ensure by inspection, and possibly by test, that they are clean and sound. Do we always ensure that they are well graded ? Do we always know what we mean by " well graded " ? Does " well graded " always mean the same thing ? Generally when the concrete is mixed we think we know by its appearance whether the aggregates are " well graded." Could we have known beforehand, even from sieve analyses ? Do the aggregates always receive even a small fraction of the care that is given to the cement ? True, the cement and water are the active ingredients, and the ratio of one to the other is of vital importance. The aggregates are merely inert fillers, but they

form about 80 per cent. by weight of the finished concrete. They deserve more care in selecting, testing, and specifying than is always devoted to them.

In particular we ought to be able to foretell the effects of variations in aggregates on the quality of concrete. We should know how the aggregates ought to be graded in order to produce a predetermined result with specified proportions of cement and water. We should know also how grading ought to be modified to allow for differences in shape of aggregates; for instance, for the difference between gravel and crushed stone. Knowing our requirements for grading, we should be able to tell from sieve analyses whether proposed aggregates are excellent for our purpose, barely acceptable, or unsuitable. This means that we should have standards and tolerances for the grading of aggregates.

A satisfactory method of specifying materials and workmanship should provide for all these points. It should tell us how to select our materials, how to proportion them, how to mix, place, and mature the concrete so as to produce a predetermined quality, and how to calculate by simple methods the quantity of each material required for a unit volume of finished concrete. Quality here refers, not to strength alone, but to density, watertightness, surface finish, and endurance.

Method Employed Satisfies Requirements.

The method to be described satisfies these requirements. Accepting the usual standards for quality of cement and water, and for cleanliness, strength and durability of the aggregates, it provides guidance for fixing the proportions of all the materials, including the water. It furnishes grading limits for gravel and crushed stone aggregates of several maximum particle sizes. These limits are guides for specifying gradings to suit different requirements, and for enabling one to tell from sieve analyses whether samples submitted are suitable. The method provides the information necessary for the complete design of mixes and shows how to calculate quantities of materials. It shows how to make the best use of available aggregates when choice is limited by local conditions, and aggregates that are not quite suitable must be used. It contains guidance on mixing, placing, and maturing. While being adaptable to use in conjunction with the ordinary specifications, it suggests some special clauses that would help both the engineer and contractor by enabling the one to specify more definitely and the other to comprehend more clearly what is required of him. It has been tested and found satisfactory in practical use under varied conditions for several years.

CHAPTER III

FUNDAMENTAL CONSIDERATIONS

Characteristics of Good Concrete.

Good concrete in the finished state should have the following characteristics:

(1) Sufficient strength for the purpose for which it is intended.

(2) Density or compactness, that is, the space occupied by the concrete should be as nearly as possible filled with solid particles of aggregate and set cement, and correspondingly free from tiny voids, air holes, and honeycombing.

(3) Suitable cement content, that is, sufficient cement to give the strength and density required and not appreciably more than is necessary.

(4) Smooth and hard exposed surfaces.

In order that these qualities may be obtained in the finished concrete corresponding properties must be present in the raw mix. Separate examination of each characteristic of the finished concrete will reveal corresponding requirements in the raw mix.

Factors Governing Strength of Concrete.

The strength of concrete depends principally on eight factors, namely:

(1) The quality of the cement.

(2) The proportion of cement in the mix.

(3) The proportion of mixing water.

(4) The cleanliness and strength of the aggregate.

(5) Adhesion of the cement to the aggregate.

(6) Adequate mixing.

(7) Proper placing.

(8) The care taken to ensure that the concrete is kept moist and at a temperature not less than 40 deg. F., while it is maturing.

The three first deal with inherent properties and the relationship of the chemically active materials; these must be dealt with at length. The fourth and fifth are obvious causes of differences of strength; very weak friable aggregates cannot be expected to make strong concretes; and smooth hard-surfaced gravels may cause a small reduction of strength. The remaining factors depend on workmanship. So far as mixing, placing, and maturing are concerned it is sufficient for the moment to say:

(1) Mixing in a power mixer should be continued for 1½ minutes from the time all the materials are in the machine;

(2) Shuttering should be oiled or well soaked with water before concrete is placed;

(3) The concrete should be so placed as to be well compacted;

(4) All exposed surfaces should be kept wet for at least seven days (and

preferably fourteen days), and kept at a temperature not less than 40 deg. F.; and

(5) Exposed surfaces should be carefully protected from drying winds and from the sun during the maturing period. (*Too rapid drying reduces strength by at least one-third.*)

If all these conditions are satisfied the main factors are quality of cement, proportion of cement, and proportion of water.

Quality of Cement.—Omitting special cements such as blast-furnace and aluminous cements, we may divide Portland cements into normal hardening and rapid hardening. Both set at about the same rate but harden (that is, gain strength) at very different rates, many rapid-hardening Portland cements having higher strengths at seven days than those of normal Portland cements at twenty-eight days. But even among themselves both normal and rapid-hardening cements differ considerably. The strength of one brand of normal cement at twenty-eight days may be one-and-a-half times that of another; and the same ratio may hold between the strengths of different brands of rapid-hardening Portland cements at seven days.

However, when attention is confined to one brand of cement, or to one consignment from the same mill, variations due to quality are minimised. If, as well, the factors of aggregate quality and workmanship are maintained constant, then the strength of concrete depends on the cement content and proportion of water.

Effect of Cement Content.—It is obvious that the strength of concrete ought to increase with cement content. A rich mix is usually very much stronger than a lean mix. It is common experience that when care is taken to make concretes of about the same consistency an increase in cement content usually causes a corresponding increase in strength.

Fig. 1 shows the results of a number of crushing tests of concretes made with various proportions of the same cement and all tested at the same age. All mixes were easily workable. While the plotted points (not shown on the graph) showed considerable differences in strength for concretes of the same cement content, they indicated clearly a general increase in strength with cement content. The general trend of the increase of strength with cement content is indicated by the smooth curve on the graph. At the same time the plotted points showed that a concrete made with 600 lb. of cement per cubic yard may not be stronger than another made with 500 lb. of cement per cubic yard, and that the strengths of two concretes made with very nearly the same cement content may differ considerably. The reason for this will become apparent when the effect of the proportion of water has been discussed.

[Note: The age at which the specimens, whose crushing strengths were plotted in *Fig.* 1, were tested is deliberately withheld to prevent the danger of associating particular strengths at a definite age with the cement contents shown. Strengths may vary so much with the type and quality of cement that a wide range of strengths may be obtained by using different cements. This diagram and others given later are intended to show the *trend* of the relationship between strength and one other variable (cement content in this case), and not to supply data that can be used in practice. Where strength is important it is generally necessary, and always advisable, to make a few preliminary tests with the cement to be used.]

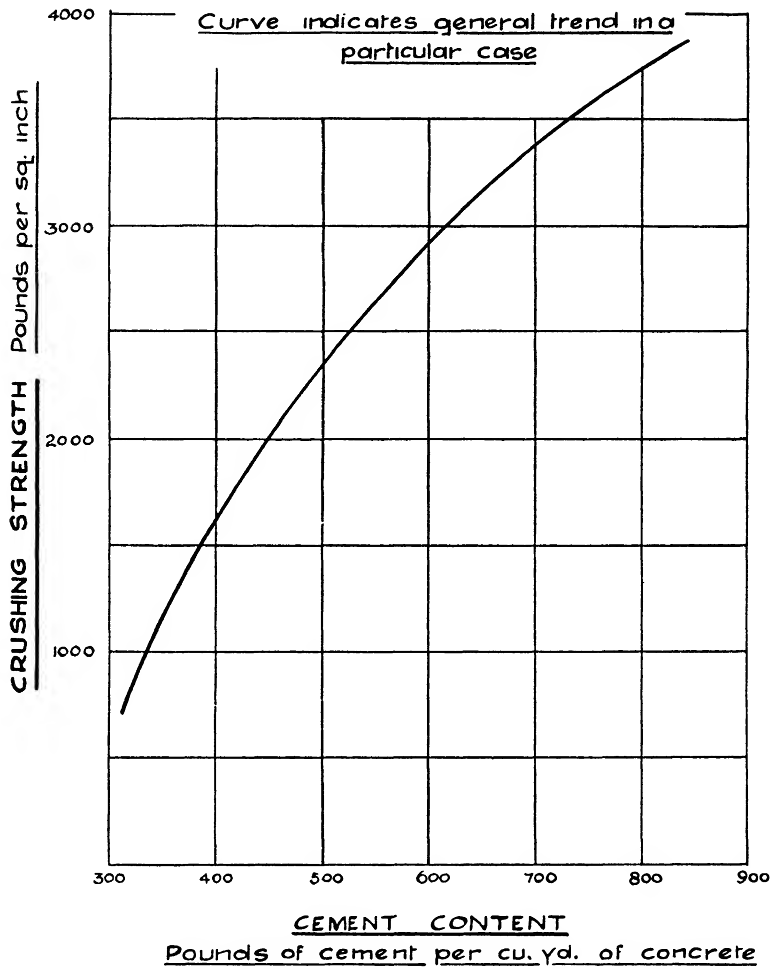


Fig. 1.—Increase of Crushing Strength with Cement Content.

Effect of Water Content.

Function of Water.—Water is required in raw concrete to produce chemical changes in the cement, to wet the aggregate, and to lubricate the mixture so as to make it easy to place. The amount of *lubricating* water used determines the consistency. In rich mixes the proportion of water required to wet the aggregate is small in comparison with that required to hydrate the cement, and the lubricating water is required mainly to lubricate the cement itself. In such rich mixes of ordinary consistency the proportion of cement to water is generally high. In lean mixes of ordinary consistency relatively larger proportions of water are required for wetting and lubricating the aggregates, and in them the proportion of cement to water is small.

For the same proportion of cement to aggregate, the proportion of water required to produce a given consistency varies with the grading of the aggregate.

More water is necessary to wet a given weight of aggregate consisting mainly of small particles than to wet the same weight of bigger particles because of the increased surface area of the greater number of small particles. Of two 1 : 2 : 4 concretes made with the same coarse aggregate, but with a very fine sand in one case and a coarse sand in the other, the one with the fine sand requires more water to make it equally workable. Again, if there is no specified proportion of water, one user of the same proportions of dry materials and the same aggregates may prefer to use more water than another. Therefore, for one reason or another, concretes made with the same proportions of cement to aggregate may have different proportions of cement to water. In the general run of concretes of widely different proportions of cement to aggregates and made with different aggregates the proportion of water varies widely. This variation and its effect are important.

Proportion of Water.—Before considering the effect of altering the proportion of water we must first consider exactly what is meant by this proportion and how to express it. At first sight it might seem most useful to measure the water as a percentage of the total weight of dry materials or as a percentage of the volume of finished concrete, as was done with the cement. A relationship might be expected between water content and strength. But no such relationship exists. Two concretes made with the same water content and different proportions of cement will have different strengths.

It is not the proportion of water relative to the whole of the dry materials that is important, but the proportion of water relative to the cement. Extra water dilutes the cement paste. Extra cement enriches the cement paste. The richer paste is the stronger.

Expressing the Proportion of Water.—Relative proportions of cement and water are expressed in several ways:

(1) Cubic feet of water to cubic feet of cement, that is, water-cement-ratio by volume.

(2) Gallons of water per standard bag of cement, that is, imperial gallons per 112 lb. of cement in British practice.

(3) Pounds of water per pound of cement, that is, water-cement-ratio by weight $\left(\frac{w}{c} \text{ by weight}\right)$.

(4) *Pounds of cement per pound of water, that is, cement-water-ratio by weight* $\left(\text{or } \frac{c}{w} \text{ by weight}\right)$.

There is a strong objection to the first method inasmuch as a volume of cement conveys no meaning unless the method of packing is specified in great detail. A fine powder such as cement cannot be measured reliably by volume. A cubic foot measure of cement may contain anything from 75 lb. to more than 95 lb. of cement according to the method of filling adopted and the fineness of

grinding of the cement. Whereas 75 lb. of a finely-ground cement will fill a cubic foot measure if it is merely poured in and smoothed off on top, more than 95 lb. can be put in by special methods of packing. In order to adopt this method of expressing the proportion of water it is necessary to fix some arbitrary weight of cement as the equivalent of a cubic foot. In effect the ratio then becomes a ratio by weight, since the weight of a cubic foot of water is constant at normal temperatures. No further reference will be made to this method.

It is common practice to base the proportions of concrete on the standard 112-lb. bag of cement. The normal measure for water is the imperial gallon (10 lb.). Therefore the second method is the most convenient for expressing the proportions of water, that is, gallons of water per 112-lb. bag of cement. A proportion so stated gives the volume of water required for a batch. Thus, if it is decided to use 6 gallons per bag and to use a two-bag batch, the amount of water to be used in the batch is 12 gallons. Also, since the weight of a gallon of water is 10 lb., the number of pounds of water in the batch is easily determined, so that this method is convenient when batching by weight is adopted.

The third method, weight of water per pound of cement, or water-cement-ratio by weight, is commonly used in English-speaking countries, and is used in the Recommendations for a Code of Practice issued by the Reinforced Concrete Structures Committee. It has one disadvantage: the relationship between the strength and the water-cement-ratio by weight is not a very simple one.

The fourth method, cement-water-ratio by weight $\left(\frac{c}{w}\right)$ has come into prominence in recent years. As will be shown later the relationship between strength and cement-water-ratio by weight is a very simple one for the normal range of mixes, provided the concrete is well compacted. Of course, cement-water-ratio is the inverse of water-cement-ratio.

Throughout this work the proportion of water will generally be given in imperial gallons * per 112-lb. bag of cement, as this is most convenient for ordinary

TABLE 1.—Conversion Table.

Imperial gallons of water per bag of cement	Equivalent water-cement-ratio by weight $\frac{w}{c}$	Equivalent cement-water-ratio by weight $\frac{c}{w}$
4	0·36	2·8
5	0·45	2·24
6	0·54	1·87
7	0·63	1·60
8	0·71	1·40
9	0·80	1·25
10	0·89	1·12
11	0·98	1·02
12	1·07	0·94
13	1·16	0·86
14	1·25	0·80
15	1·34	0·75
16	1·43	0·70

* 1 imperial gallon = 1·201 United States gallons.

Also $\frac{\text{Imperial gallons of water}}{\text{112 lb. of cement}} = \frac{\text{U.S. gallons of water}}{\text{U.S. 94-lb. bag of cement}}$ as nearly as makes no difference.

purposes. But where the effects of water content on strength are discussed, cement-water-ratio by weight will be used.

Conversion from one to another of these methods of stating the relative

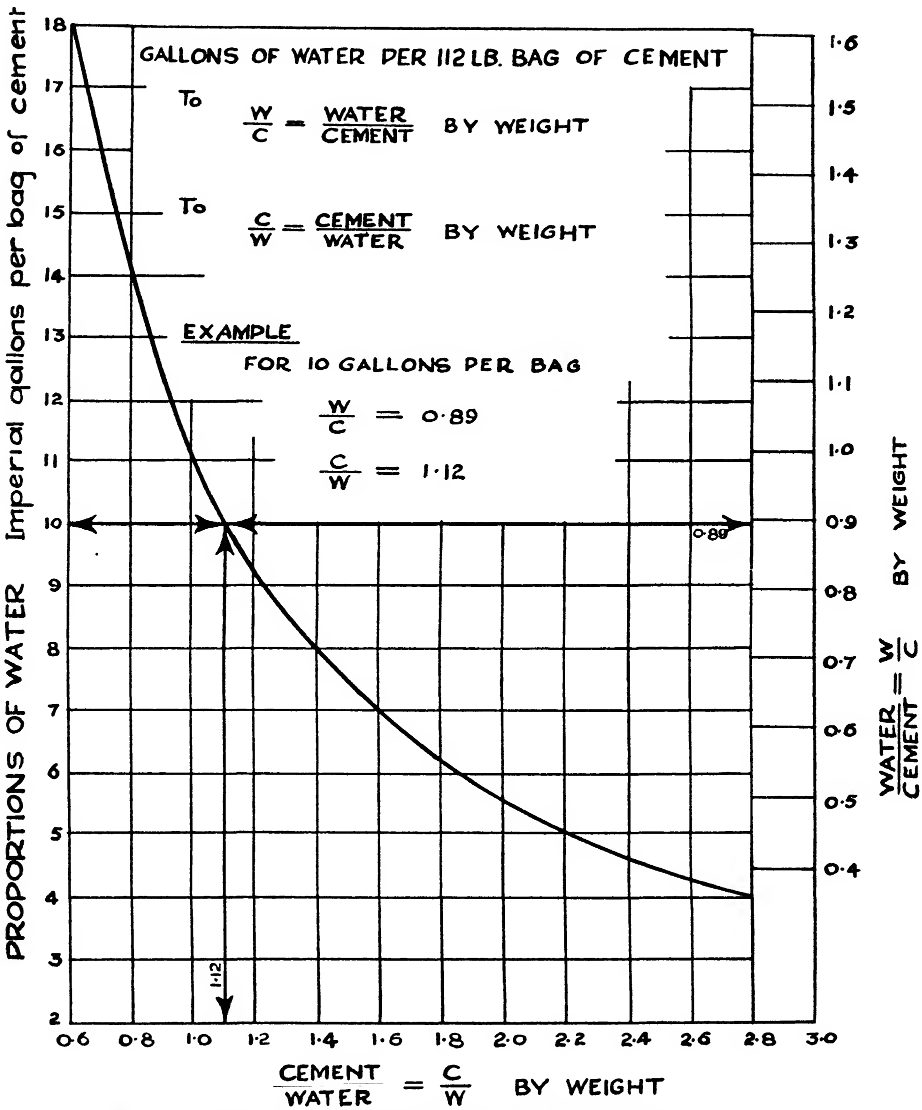


Fig. 2.—Diagram for the Conversion of Water-Cement-Ratio to Cement-Water-Ratio.

proportion of water and cement can be made by a simple calculation. For the reader's convenience the relationship between methods (2), (3), and (4) is given in *Table* 1, in which the values of $\frac{W}{C}$ and $\frac{C}{W}$ corresponding to various numbers

of gallons per bag are tabulated. This table is useful only for converting from gallons per bag to one of the other methods of expressing the proportions. Conversion in any direction is facilitated by the use of *Fig.* 2.

In *Fig.* 2 gallons per bag are given vertically on the left-hand side, and a scale of water-cement-ratios by weight vertically on the right-hand side. These are so arranged that the value of $\frac{W}{C}$ by weight corresponding to a particular number of gallons per bag is horizontally opposite that number. Thus, going across horizontally from 10 gallons per bag, one reads 0·89 on the $\frac{W}{C}$ scale. By going horizontally from either vertical scale to the curve and then vertically downwards to the bottom one finds the corresponding value of $\frac{C}{W}$. Thus for 10 gallons per bag $\frac{C}{W} = 1{\cdot}12$; or, crossing horizontally from $\frac{W}{C} = 0{\cdot}5$ to the curve and then going down vertically, one reads, $\frac{C}{W} = 2{\cdot}0$. To convert $\frac{C}{W} = 1{\cdot}4$ into gallons per bag the vertical from 1·4 on the bottom line is followed up to the curve and then, crossing horizontally, 8 gallons per bag is read on the left-hand scale.

Effect of Proportion of Water on Strength.

It has been shown that, in general, strength increases with the proportion of cement in the concrete. On examining the proportions of cement and water in the general run of mixes it will be found that the proportion of cement to water is much higher in the rich mixes than in the lean. The reason is that a smaller proportion of water relative to the cement is required to produce the same consistency in a rich mix than is necessary in a lean mix. Thus, in two concretes containing respectively 620 lb. and 400 lb. of cement per cubic yard the ratios by weight of cement to water are 1·8 in the rich mix and 1·0 in the lean mix. It is really the proportion of the cement to the water that is responsible for the higher strengths of rich mixes, and not merely the proportion of cement.

In the range of mixes commonly used where strength is important the proportion of water varies from about 12 gallons per bag to about 5 gallons per bag. The corresponding range of cement-water-ratio by weight is from a little less than 1·0 to 2·2.

> *Over this range and provided the concrete is well compacted the strength of the concrete increases in direct proportion to the increase in cement-water-ratio by weight.*

Normal Portland Cement.—*Fig.* 3 shows the relations between the strengths at seven days and twenty-eight days and the cement-water-ratio by weight for a certain brand of normal Portland cement. The lower line is for seven-day strengths, and the upper line for twenty-eight-day strengths. In each case the results of the tests defined a straight line very closely between the limits shown. Beyond these limits the strengths were below the values which would be given by producing the straight line.

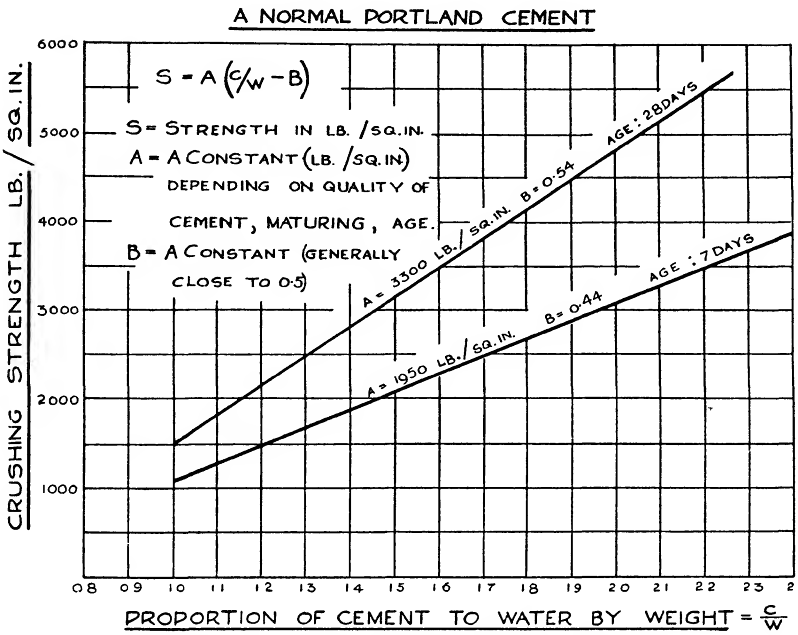


Fig. 3.—Strength and Cement-Water-Ratio.

Rapid-Hardening Portland Cement.

Fig. 4 is a diagram for concretes made with rapid-hardening cements tested at four days and seven days. The upper pair of curves shows the relation between the strength and the cement-water-ratio obtained with a rapid-hardening Portland cement which gives exceptionally high strengths. The other pair is for a rapid-hardening Portland cement of quality nearer to the average.

Figs. 3 *and* 4 *are not to be used in design.* The lines on both *Figs.* 3 and 4 merely indicate the general nature of the relationship between strength and the proportion of cement to water by weight. They should not be applied in practice. In a particular case a set of tests should be made with the brand of cement that is to be used and at the consistency likely to be used on the works. Works conditions should be simulated as closely as possible. In these tests three values of $\frac{C}{W}$ (1·0, 1·5, and 2·0, or 1·2, 1·5, and 1·8) should be used and the strength plotted against the values of $\frac{C}{W}$. If the concretes are fully compacted the three points will lie on or close to a straight line.

The formula that represents any one of the straight lines in *Figs.* 3 and 4 is of the form

$$S = A\left(\frac{C}{W} - B\right) \quad \quad (1)$$

where S = strength in lb. per square inch ;

A = a constant (lb. per square inch) depending on the quality of the cement, maturing conditions, and the age of the concrete ; and

B = a numerical constant.

The values of A and B are written on the various lines in *Figs.* 3 and 4. It will be noticed that the values of B are all close to 0·5, especially in *Fig.* 4. This occurs commonly, and in most cases the error introduced by putting $B = 0·5$

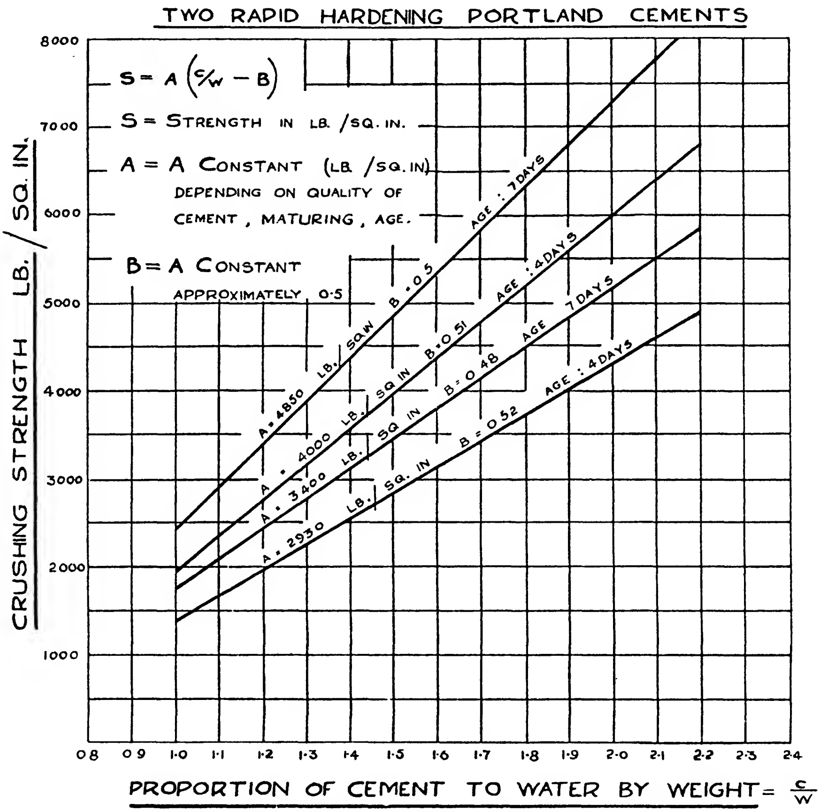


Fig. 4.—Strength and Cement-Water-Ratio.

is small. Also the value of A may be taken at the nearest (lower) 100 lb. per square inch, that is, if it is calculated to be 2930, it may be taken as 2900. Thus the formula for the lowest line in *Fig.* 4 may, with negligible error, be written

$$S = 2900\left(\frac{c}{w} - 0·5\right) \text{ lb. per square inch} \quad . \quad . \quad . \quad . \quad (2)$$

Also, since strengths on the works may easily vary 10 per cent. above or below the average, a reduction of at least 10 per cent. may be made in the value of A. For example, equation (2) might be replaced by

$$S = 2600\left(\frac{c}{w} - 0·5\right) \text{ lb. per square inch} \quad . \quad . \quad . \quad . \quad (3)$$

When the relationship between strength and cement-water-ratio has been established, and the value of $\frac{c}{w}$ for any particular purpose has been decided, the corresponding number of gallons of water per bag of cement can be read from *Fig.* 2 (in the absence of *Fig.* 2, divide 11·2 by the value of $\frac{c}{w}$ in order to get the corresponding number of gallons per bag).

Variation of Strength with Age.

The strength of a normal concrete at twenty-eight days is usually between $1\frac{1}{3}$ to $1\frac{1}{2}$ times its strength at seven days—about $1\frac{1}{3}$ times for the weaker cements and leaner mixes, and about $1\frac{1}{2}$ times for stronger cements and medium mixes. In rich mixes the ratio becomes higher and may reach $1\frac{2}{3}$. It is useful to remember these figures because tests are often made at seven days, even though the concrete is not put into service until twenty-eight days.

The strength at seven days of a rapid-hardening Portland cement varies from $1\frac{1}{8}$ to about $1\frac{1}{3}$ times the strength at four days, and from about $1\frac{1}{3}$ to nearly twice the 3-days' strength. The ratio of the 28-days' strength to the 7-days' strength lies roughly between the same limits for rapid-hardening as for normal Portland cements, that is, between $1\frac{1}{3}$ and $1\frac{1}{2}$ to 1.

Density.

The properties of concrete that determine its durability in exposed situations are its density and surface finish. Concrete that is dense and impermeable and that has a smooth, hard, impervious surface will endure where porous and permeable concrete may disintegrate in a very short time.

The author has seen poor concrete destroyed in a few months in a place where it was exposed to severe attack by peaty water. Well-placed dense concrete in the same exposure suffered no more damage than etching of the surface during a period of five years. For all concrete exposed to severe weathering conditions or attack by water, and for concrete in water-retaining structures, density and hard smooth surfaces are most important.

Density Depends on Grading.—Density depends mainly on the grading of the mixture of aggregates and cement. The dry mix of aggregates and cement must be so graded that, when the proper amount of water is added, the mixture will be sufficiently workable for the method of placing, and the resulting concrete will have a high weight per cubic foot. The best grading of the aggregate alone varies with the proportion of cement. Consider a mix of the proportions of 1 bag of cement to 4 cu. ft. of mixed aggregate (combined fine and coarse). A certain grading of the aggregate is necessary in this case in order that the mixture of cement and aggregate may be suitably graded for making workable and dense concrete. If the same aggregate is used in a mix of the proportions of 1 bag of cement to 8 cu. ft. of aggregate there will be a deficiency of fines, because of the smaller proportion of cement. The reduction in cement must then be balanced

by increasing the proportion of fine aggregate in order to avoid harshness and honeycombing in the lean concrete.

On the other hand, an aggregate graded to suit a lean mix contains so much fines that it will not make a dense concrete when it is used in a rich mix because more and leaner mortar is formed, and this is not as dense as the properly graded concrete. But it will then make a fat, workable concrete. The grading of the aggregate must suit the proportion of cement in order that both workability and high density may be obtained simultaneously.

Density Affected by Proportion of Water.—Density depends also on the proportion of water. When the proportion of cement and the grading of the aggregates are constant any increase in the quantity of water beyond that necessary to make the concrete easy to compact reduces the density. The excess water segregates into little drops, forming small pockets of water throughout the mass. These ultimately dry out, leaving air spaces. Since concrete in severe exposures should be as dense as possible, it is important to avoid excess water in making concrete that is to be exposed to destructive agencies such as sea-water, acid waters, frost, etc.

Weight per Cubic Foot a Measure of Density.—Weight per cubic foot is a sufficient indication of density provided the specific gravity of the aggregate is known. Good concrete made with $\frac{3}{4}$-in. aggregate having a specific gravity of about 2·65 should weigh more than 146 lb. per cubic foot. This weight is for rich and medium mixes. With $1\frac{1}{2}$-in. aggregates the weight should exceed 147 lb. per cubic foot. For aggregates of higher specific gravities the weights should be increased.

Works Test.—A most useful works test can be made by using a strong cylindrical bucket of $\frac{1}{2}$ cu. ft. capacity (10 in. deep by $10\frac{1}{2}$ in. diameter), filling it flush with concrete by the same methods as are employed in filling the shuttering, and weighing. The weight of the bucket being known, the weight of a $\frac{1}{2}$ cu. ft. of the concrete is determined. A spring balance capable of weighing up to 100 lb. suspended in a convenient place completes the equipment.

So long as the concrete remains easy to place by the methods employed and the weight per cubic foot is above the prescribed limit (146 *to* 147 *lb. per cubic foot, or as otherwise specified*), *both the workability and density of the concrete are satisfactory.*

Suitable Cement Content.

It is scarcely necessary to stress the fact that from the point of view of economy

No more cement should be used than is necessary to produce the required workability, density, surface finish, and strength.

Economy is not the only argument for reducing the cement. Shrinkage and the consequent danger of cracks can be reduced by keeping down the cement content. It will be shown that workability, density, and surface finish can be well maintained in comparatively lean concretes, provided the aggregates are carefully chosen and proper methods of placing are adopted. Where strength and resistance to weathering are not important lean mixes are satisfactory.

However, in most of the important uses of concrete either high strength or density is required in the finished concrete and easy workability in the raw mix. To get workability with the high cement-water-ratio that is necessary to give high strength a mixture rich in cement must be used.

Experience and practice have established the cement contents suitable for different conditions ranging from highly-stressed reinforced structural members to mass concrete carrying very little load. But the common practice of describing concrete by the proportions of cement to fine aggregate to coarse aggregate (1 : 1½ : 3, 1 : 2 : 4, etc.) is unsatisfactory insofar as it gives no direct indication of the proportion of cement in the finished concrete. In fact, it fails to describe the cement content accurately, because the latter depends on the nature of the aggregates, especially on the shape and grading of the aggregate. It is much more satisfactory to state directly the weight of cement per unit volume of finished concrete; this is conveniently stated as so many pounds of cement per cubic yard of concrete. Here the cement content is clearly specified. As soon as the volume of concrete to be made is known the weight of cement required is also known. The proportion of aggregate is yet to be found.

In the method of designing mixes described later account is taken of the grading of the combined aggregate. For each proportion of cement to aggregate there is sought a combination of fine and coarse aggregates that will have a grading suitable for making dense and workable concrete with that proportion of cement. The combined aggregate being so graded, there is a definite relationship between the cement content of the finished concrete and the proportion of cement to combined (that is, mixed) aggregate. Therefore, in this system the cement content of the finished concrete fixes the ratio of cement to combined aggregate. Consequently, the weight of cement and the volume of mixed aggregate required can be readily calculated when the volume of concrete to be placed is known. Since the grading of the mixed aggregate is also fixed by the cement content per cubic yard of concrete the proportions of fine and coarse aggregates can also be calculated. Everything follows from the specified weight of cement in a cubic yard of finished concrete.

Take a concrete specified to contain 630 lb. of cement per cubic yard. Assume that the aggregates are to be a sand passing a $\frac{3}{16}$-in. sieve and a gravel passing a $\frac{3}{4}$-in. sieve and retained on a $\frac{3}{16}$-in. sieve. Experience shows that when properly graded sand and gravel are combined in suitable proportions, and the combined aggregate is mixed with cement in the proportions of 4·9 cu. ft. of aggregate to 112 lb. of cement, the resulting concrete contains about 630 lb. of cement per cubic yard. Therefore, to produce a cubic yard of concrete there are required 630 lb. of cement and

$$4{\cdot}9 \times \tfrac{630}{112} = 27{\cdot}6 \text{ cu. ft. of dry mixed aggregate.}$$

For sand and gravel particles of average specific gravity, and with the proper grading, this would weigh about 108 lb. per cubic foot (loose). That is, the total weight of aggregate required is 2970 lb. It will be shown later that the proper grading requires the aggregate to consist of 36·5 per cent. of sand by weight and 63·5 per cent. of gravel. The quantities of dry materials required for a cubic yard of concrete are, therefore, 630 lb. of cement, 1084 lb. of dry sand, and $2970 \times \frac{63{\cdot}5}{100} = 1886$ lb. of dry gravel. If the sand contained about 5 per

cent. of water and the gravel about 1 per cent., the corresponding weights would be 630 lb. of cement, 1140 lb. of damp sand, and 1900 lb. of damp gravel.

From these figures the total quantities of cement, sand, and gravel required for the contemplated work can be calculated approximately. When samples of the aggregates to be used are supplied more accurate quantities can be calculated.

Equivalents of Arbitrary Proportions.

Table 2 shows the equivalents of the arbitrary proportions 1 : 1½ : 3, 1 : 2 : 4, and other proportions containing twice as much gravel as sand in terms of the cement content per cubic yard, the proportion of cement to mixed aggregate,

TABLE 2.

Arbitrary proportions	Lb. of cement per cubic yard (average values)	Cubic feet of dry mixed aggregate to 112 lb. cement	Proportion of water. Gallons per 112 lb. of cement
1 : 1 : 2	870	3·3	5
1 : 1½ : 3	630	4·9	5¾ to 6½
1 : 2 : 4	510	6·25	7 to 8½
1 : 2½ : 5	420	7·75	8½ to 10½
1 : 3 : 6	330	9·50	10 to 13

and the proportion of water (assuming that measurements are by loose volume; that is, gravel shovelled into measuring boxes without compacting). The data are for aggregates graded to make dense and workable concrete, and may not hold closely for aggregates of other gradings.

The weights of cement per cubic yard of concrete given in this table are average values. They vary by as much as 5 per cent. with the size and shape of the aggregate. The proportions of water given make concretes that can be easily rodded into place. Exact figures cannot be given for the weight of cement per cubic yard and the proportion of water, since both depend on the grading, shape, and maximum size of the aggregates. This will be dealt with in more detail later.

It is noteworthy that dry mixed aggregates graded to produce dense and workable concretes frequently weigh about 112 lb. per cubic foot when filled loosely (without tamping or shaking) into a container. That is, the weight of 1 cu. ft. of aggregate is nearly the same as that of a bag of cement. Therefore the figures in the third column indicate not only the number of cubic feet of aggregate to one bag of cement but also roughly the ratio of aggregate to cement by weight.

Surface Finish.

Smoothness and hardness of surfaces depend on workability and grading of the aggregates.

The workability must be such as to enable smooth surfaces to be obtained with the methods of placing adopted. Hardness of surface depends partly on not having too much fine material in the aggregate, and partly on adequate moist maturing and prevention of drying out of the surface during the hardening period. There should be no more fine material in the aggregate than is necessary for workability. Surfaces should be kept wet for at least fourteen days.

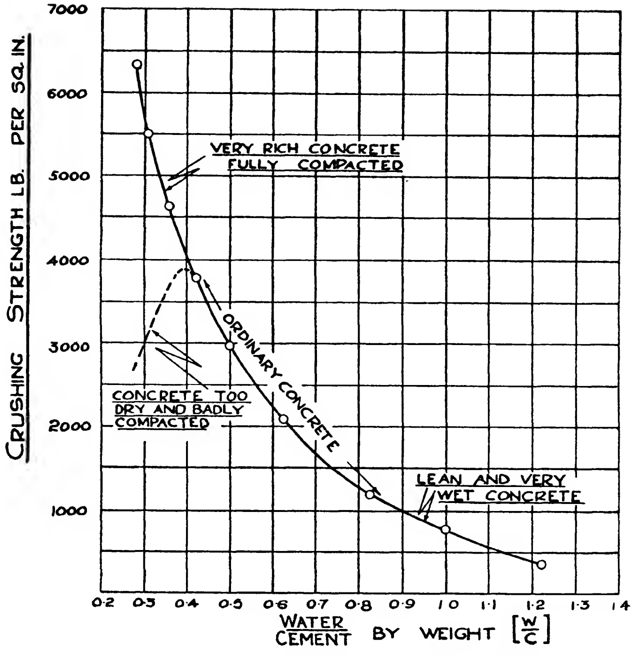


Fig. 5.—Strength of Concrete with Different Ratios of Water to Cement $\left(\frac{w}{c}\right)$.

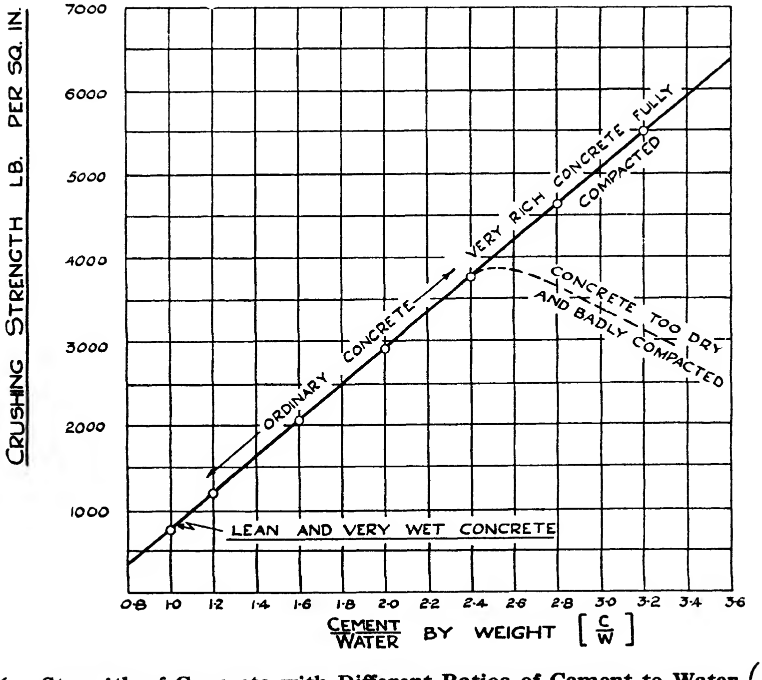


Fig. 6.—Strength of Concrete with Different Ratios of Cement to Water $\left(\frac{c}{w}\right)$.

Reason for Preference for Cement-Water-Ratio $\left(\frac{c}{w}\right)$.

WATER-CEMENT-RATIO.—A curve showing the strength of concrete with different water-cement-ratios, that is, different proportions of *water to cement*, takes the form shown diagrammatically in *Fig.* 5. The figures at the bottom are the proportions of water expressed as fractions of the weight of cement. It will be seen that when the proportion of water is very small (left-hand side of the diagram) the strength may be either very high or quite low. This depends on whether the concrete is made rich enough in cement to allow of complete compaction even when little water is used, or whether it is so proportioned that the amount of water used is insufficient to make the mix wet enough to allow complete compaction. In the former case the strength continues to rise until the water-cement-ratio is reduced to about 0·3. In the latter case the strength falls off rapidly when the water-cement-ratio falls below about 0·4. When the proportion of water is still further reduced there is not enough water present to wet the aggregates and hydrate the cement, and the strength falls off very rapidly. The diagram shows that, in either case, the strength decreases as the water-cement-ratio is increased beyond 0·4, and the more water added the lower the strength until the cement paste becomes so dilute that it has hardly any strength. When water content is expressed as the water-cement-ratio the strength curve always takes the general shape of the curve in *Fig.* 5. The equation or formula of this curve is not simple, and calculations with it require the use of logarithms. To determine the shape of the curve for any brand of cement it is necessary to make tests with concretes having several different water-cement-ratios.

CEMENT-WATER-RATIO.—It is more convenient to express the proportion of water as the cement-water-ratio, that is, the proportion of the weight of cement to the weight of water. This is the reverse or inverse of the water-cement-ratio. The proportions of water and strengths used in *Fig.* 5 are replotted in *Fig.* 6, in which the strengths are plotted against cement-water-ratios. In this diagram the strength rises with increasing cement-water-ratio, so that the diagram expresses our ordinary impression of increasing strength with increase in cement. But *the real advantage of this method of plotting is that the points lie on a straight line*, at least within the range of cement-water-ratios ordinarily used. Outside this range the position of the points depends on the compaction of the concrete. The advantages of a straight-line relationship are that it can be expressed by a very simple formula and that the position of the line can be determined from tests of concretes made with two cement-water-ratios and checked by tests of concrete made with an intermediate ratio.

On comparing *Figs.* 5 and 6 it will be seen that the two diagrams give the same information. Consider a batch of concrete containing 100 lb. of cement and 60 lb. of water. Here the water-cement-ratio is 0·6, and *Fig.* 5 gives the corresponding strength as 2230 lb. per square inch. The corresponding cement-water-ratio is 100 divided by 60, or 1·67, and, as nearly as it can be read, *Fig.* 6 gives the corresponding strength as 2230 lb. per square inch. *Fig.* 6 is easier to draw, and it can be constructed reliably from fewer tests than are necessary for drawing the curve of *Fig.* 5. Of course, the scales of either diagram can be arranged to give any desired degree of accuracy in reading.

CHAPTER IV

QUALITY OF MATERIALS

Cement.—Portland cement should comply with the requirements of the British Standard Specification for Portland Cement. High-alumina cements and other special cements, which may be required for special works, should be subjected to suitable tests.

Water.—Water should be clean and free from deleterious matter, such as oil, acid, alkalis, sugar, and vegetable matter.

Aggregates.—Aggregates should be natural sand and gravel, crushed natural stone, crushed brick, or such other artificial aggregates as may be allowed in special cases. All aggregate particles should be hard, strong, and durable, free from flat and elongated particles, and free from clay, organic matter, soluble sulphates, and all other materials likely to delay the setting of the cement, reduce the strength of the concrete, or attack the reinforcement.

FINE AGGREGATE.—The fine aggregate should consist preferably of siliceous natural sand. It should be of such a size that it will pass through a $\frac{3}{16}$-in. mesh, and not more than from 1 to 8 per cent. should pass a No. 100 sieve according to whether the concrete is to be rich or lean. Sands dredged from lakes should be tested for deleterious organic matter, even though they appear perfectly clean.

Crusher fines smaller than $\frac{3}{16}$ in. are not usually a desirable substitute for natural sand, but circumstances may arise in which their use is unavoidable. Great precautions should then be taken to avoid using excess of extreme fines or flour.

Small lumps of clay, if present, should not exceed 1 per cent. by weight. Silt, as measured according to British Standard Specification No. 812, 1938, should not exceed 3 per cent. (see Appendix 5).

COARSE AGGREGATE.—Coarse aggregates should consist of particles all retained on a $\frac{3}{16}$-in. sieve and graded from that size to the maximum size specified for the work. The usual maximum size for reinforced concrete is $\frac{3}{4}$ in., but in special cases this may be increased to $1\frac{1}{2}$ in. For mass concrete the maximum may be $1\frac{1}{2}$ in., 2 in., 3 in., or even larger.

Crushed stone should be free from dust.

Gravels dredged from polluted rivers should be washed. Even when washed, they should be tested before use.

Pit-run gravels containing fines may be used in certain cases. Precautions should be taken to ensure that serious variations in grading do not occur.

For first-class work all aggregates should be washed.

If there is any doubt about the quality of aggregates or water, simple tests, which are described in most standard reference books, should be carried out on the works. Otherwise samples of the materials should be sent to a laboratory for examination.

The gradings of both fine and coarse aggregates will be dealt with in detail later.

Throughout the remainder of this book we will be concerned mainly with the properties of the materials which affect their proportioning. We will assume that the cement is of the specified quality, that the water is pure, and that aggregates are clean, strong, durable, free from flat and elongated particles, and free from deleterious materials.

Shape of Aggregates.—The statement that aggregates are assumed to be free from flat and elongated particles requires more elaboration. Particles of gravel and natural sand vary from almost perfect spheres to thin circular or elliptical flat discs. Nearly spherical gravel and sand particles make concrete that is more readily compacted than concrete made with flat particles. One can easily understand that it would be much easier to compact a concrete made of marbles of assorted sizes than one made with assorted coins. Many of the particles in some beach gravels are not unlike coins in shape. Similarly with crushed stone: nearly cubical particles are better than elongated, flat, and flaky particles.

Concrete made with gravel containing a large proportion of flat stones or with elongated and flaky crushed stone tends to be harsh. To overcome the harshness more sand and more water are added. The increase in the proportion of water weakens the paste and lowers the density. Also the very thin particles of gravel and crushed stone are easily broken. Consequently such concrete tends to be much weaker than concrete with the same cement content made with rounded or cubical particles.

The writer has had occasion to make comparative tests of concrete made with crushed stone containing many elongated and flaky particles and concrete made with well-shaped aggregates. Gradings, proportions of cement and water, and other variables were kept the same. The concrete made with the badly-shaped aggregate was weaker than the other and the fractures showed very numerous pieces of broken aggregate. It is obvious that badly-shaped aggregates should be avoided. The difficulty is to classify shapes and to decide which should not be used.

British Standard Specification No. 812, 1938, see Appendix 2 (p. 89), describes a method of measuring shape and determining the percentage by weight of flaky and elongated material in a sample of aggregate. A particle is said to be flaky when its thickness is less than 0·6 of its sieve size, and to be elongated when its length exceeds 1·8 times its mean sieve size. A sample of the coarse aggregate is sieved on the following set of B.S. sieves (having square openings), 2 in., 1½ in., 1 in., ¾ in., ½ in., ⅜ in., and ¼ in. The mean sieve size of a particle is the mean of the two adjacent sizes of sieves through one of which the particle passes and on the other of which it is retained.

Example.—Particles which pass a ¾-in. B.S. sieve and are retained on a ½-in. sieve have a mean sieve size of 0·625 in. A particle of this mean sieve size is said to be flaky if its thickness is less than 0·375 in. (0·625 × 0·6) and to be elongated if its length is greater than 1·12 in. (0·625 × 1·8). Limit gauges for thickness and length are described in the specification.

The specification deals solely with methods of measuring and describing shape, and describes the standard method of sampling, testing, and determining

the percentages by weight of flaky and elongated particles. Only these percentages are reported.

When the flake sorter and the length gauge are being used a sample may be divided into four shape groups or classes as follows:

	Per cent.
(A) Those which are neither flaky nor elongated (that is, well-shaped) .	. *a*
(B) Those which are flaky only	. *b*
(C) Those which are elongated only	. *c*
(D) Those which are both flaky and elongated	. *d*
Total	100

A full description of the sample would require the statement of the four percentages *a*, *b*, *c*, and *d*, and may be desirable for some purposes. However, the research on which the specification is based has shown that so full a description is unnecessary for ordinary purposes, and that only the total percentage of flaky material ($b + d$) and the total percentage of elongated material ($c + d$) are necessary. The truth of this is illustrated in the following example, in which the two methods of stating the results of shape measurements of a number of aggregates are placed side by side.

	Full description				British Standard description	
	Per cent. well shaped	Per cent. flaky only	Per cent. elongated only	Per cent. both flaky and elongated	Per cent. flaky	Per cent. elongated
Gravel No. 1 (¾ in. to ¼ in.) . .	67	10·8	17	5·3	16·1	22·3
Gravel No. 2 (¾ in. to ¼ in.) . .	67·5	11·1	20	1·4	12·5	21·4
Gravel No. 3 (¾ in. to ¼ in.) . .	44·9	22·2	29	4	26·2	33
Gravel No. 4 (¾ in. to ¼ in.) . .	29·2	22·4	34·4	14	36·4	48·4
Crushed gravel No. 1 (¾ in. to ¼ in.)	67·7	8·5	23·8	3	11·5	26·8
Do. do. (¾ in. to ¼ in.) . .	71	5·3	21·4	2·3	7·6	23·7
Crushed gravel No. 2 (¾ in. to ¼ in.)	66·4	11	21·3	1·3	12·3	22·3
Crushed stone No. 1 (¾ in. to ¼ in.)	24·3	10·5	54·4	10·8	21·3	65·3
Crushed stone No. 2 (¾ in. to ¼ in.) exceptionally badly shaped . .	7·3	13·2	50·8	28·7	41·9	79·5

Easily workable concrete can be made with each of the gravels Nos. 1, 2, and 3. Gravel No. 4 has the reputation of requiring more sand than is necessary with average gravels in order to make workable concrete. Crushed gravel No. 1 is from the same pit as gravel No. 3 and is produced by crushing stones retained on the ¾-in. screen at the pit. The material bigger than ⅜ in. in this is of better shape than that between ⅜ in. and ¼ in. Crushed stone No. 1 is a commercial product in which the presence of elongated particles is noticeable. Crushed stone No. 2 is extremely badly shaped and quite unsuitable for use in concrete.

Comparison of the two methods of description shows that either would classify the samples in almost the same order of merit, and that any difference of placing would occur only for samples of nearly the same general shape, for example, crushed gravels No. 1 and No. 2. This comparison is sufficient to indicate that the description in the B.S.S. gives as good an indication of differences in shape

in the materials as the full description. It has the advantage that it uses only two sets of index numbers instead of the four required by the other method.

It is not possible to state what limiting percentages of flaky and elongated material would render an aggregate unsuitable for use in concrete. For the present the most useful application of this specification will be for comparison of samples, and *particularly for determining whether subsequent deliveries are of as good shape as preliminary samples.*

CHAPTER V

MEASUREMENT OF MATERIALS

Cement.—As already stated, cement may weigh anything between 75 lb. and 95 lb. per cubic foot according to its fineness and the method of filling the measure. Volume measurements of cement are unsatisfactory. All measurements of cement should be by weight, and are most conveniently made by taking the 112-lb. bag as the unit.

Water.—Water may be measured either by weight or by volume.

Aggregates.—On works that are big enough to justify batching machinery, aggregates may be measured by weight. Allowance should be made for the weight of water carried by the aggregates, especially when fine sand is used. There are many methods of doing this. The simplest is by drying a weighed sample in an ordinary double-cooker, and weighing it again when dry. On smaller works aggregates are usually measured by volume.

Bulking of Sand.—The volume occupied by fine aggregate depends on its water content. *When dry it occupies a smaller volume than when damp; and when saturated with water it again occupies the same volume as when dry.* The volume occupied by damp sand may be more than one-third in excess of that occupied by the same sand when dry. The maximum amount of this bulking and the percentage of water that produces it depend on the fineness of the sand. The finer the sand the greater the bulking.

Fig. 7 contains two bulking curves showing the percentage increase of volume of a medium fine sand. One is for measurements by loose volume, that is, by simply filling into the measure without shaking or vibration; the other is for measurements made by shaking and packing to refusal. In each case a water content up to 14 per cent. increased the volume, but the percentage increase in volume was much greater with the "loose" method of measuring. Also, maximum bulking occurred with 9 per cent. of water when the measure was filled loosely, and with $6\frac{1}{2}$ per cent. of water when packing was adopted.

Incidentally this diagram also illustrates the variation of solid particles in a given measure filled with sand by different methods. In this particular case the packed dry sand occupied only $87\frac{1}{2}$ per cent. of the volume occupied by the same weight of dry sand placed loosely in the measure. Therefore, the maximum volume occupied by the damp sand when packed was only $114 \times 0{\cdot}875 = 99{\cdot}7$ per cent. of the *loose volume of the dry sand.*

Fig. 8 shows some of the data of *Fig.* 7 presented in another form. Comparison of A and B shows that a given weight of dry sand occupies less volume when packed (B) than when loosely placed in the measure (A). Therefore, packed dry sand (as might be expected) weighs more per cubic foot than loose dry sand.

Comparison of A and C shows that if equal weights of this sand are taken,

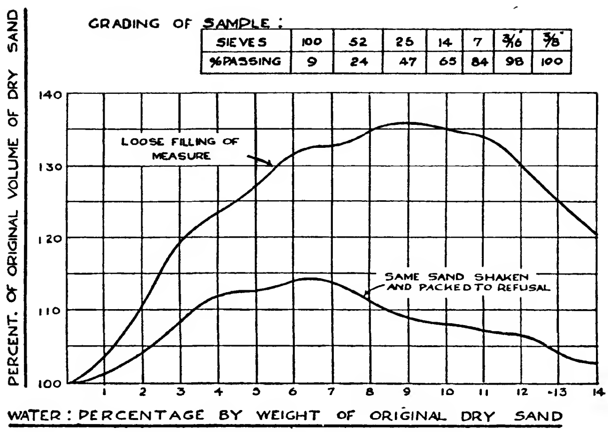


Fig. 7.—Bulking of Fine Sand.

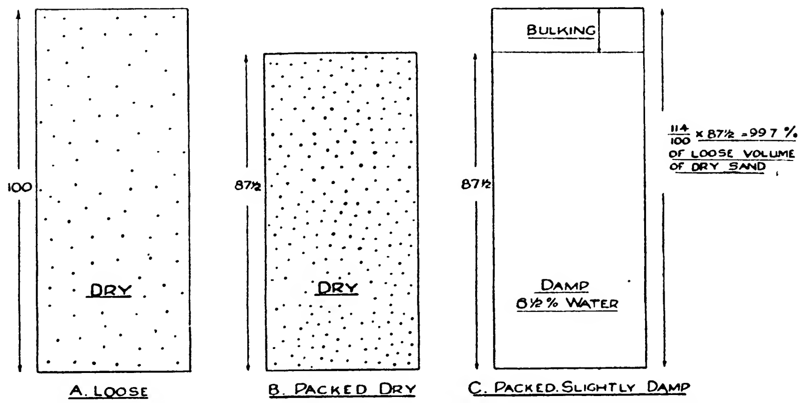


Fig. 8.—Volumes Occupied by the Same Weight of Sand Particles under Different Conditions.

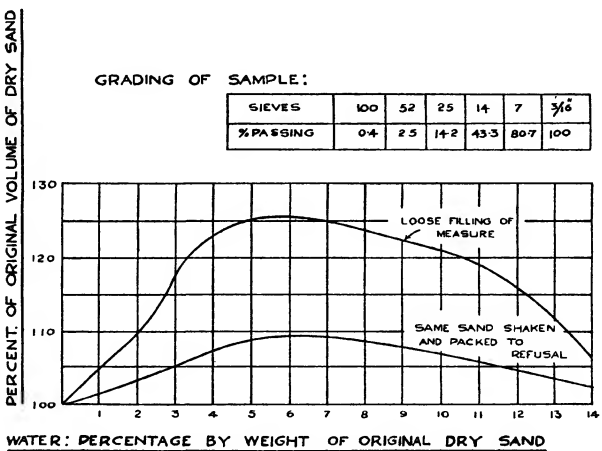


Fig. 9.—Bulking of Coarse Sand.

and if one is measured dry and loose, and if the other is dampened (with $6\frac{1}{2}$ per cent. of water) and packed into the measure, both occupy nearly the same volume.

Comparison of *Figs.* 7 and 8 shows that the original loose volume of dry sand represented by 100 units in A in *Fig.* 8 may occupy any volume between $87\frac{1}{2}$ and 136 units (maximum bulking in *Fig.* 7) according to the method of packing adopted and the amount of water carried by the sand.

> *If the sand is saturated with water it occupies the same volume as when dry provided that the same method of filling the vessel is adopted in each case.*

Fig. 9 contains a pair of bulking curves for a coarse sand. For the same method of filling the measure coarse sand bulks less than fine sand, and maximum bulking occurs with a smaller water content.

Since proportions are generally based on volumes of *dry* aggregates it is important to make proper allowance for bulking. The " Rapid Sand Tester " referred to already is a convenient and simple instrument, which enables one to determine quickly and easily the extra volume of damp sand which should be used in order to get the amount that would fill the measure if the sand were dry.

> *From the contractor's point of view it is important to make the proper allowance for bulking, because it increases the yield of concrete per bag of cement, and therefore reduces the unit cost of the concrete. From the engineer's point of view it is important because the proportion of sand specified is sometimes essential to obtain sufficient workability, and the absence of some of it may cause bad surfaces and honeycombing.*

Loose and Packed Volumes.—The weight of aggregate in a container of given volume depends on the method of filling. For example, a coarse aggregate simply shovelled into a measure without any special packing weighed 98 lb. per cubic foot. This was its weight per cubic foot when " loose." The same aggregate carefully tamped and shaken down in the same measure weighed 109 lb. per cubic foot. This was its weight per cubic foot when " packed." Throughout the following notes, volumes will be understood to mean loose volumes unless otherwise stated.

Measurements by Weight Most Accurate.—*Measurements by weight are the most accurate.* Unfortunately they can only be used on jobs that are big enough to bear the cost of the necessary batching apparatus.

Voids in Aggregates.

Reference must be made to measurements of voids in aggregates, because these have been used as a basis for deciding proportions for concrete, and are still used by some, even though this method of proportioning was shown to be of no value many years ago. The voids in an aggregate are measured by filling a vessel of known volume with the aggregate and adding water until the measure is full of aggregate and water, at the same time measuring the volume of water added. The ratio of the volume of water added to the volume of the measure, expressed as a percentage, is the percentage of voids in the aggregate.

The percentage of voids so determined depends on the way in which the aggregate is put into the vessel; that is, whether it has been put in loosely or packed, at least for coarse aggregates. In the case of sand, a measured volume of water should be put into the vessel first and the sand put into the water, adding measured quantities of water when necessary in order to keep the water just flush with the surface of the sand while the vessel is being filled.

The principle of the method of proportioning is that the voids in the coarse aggregate are filled with sand and that the voids in the sand are filled with cement. The fallacy is that the measured voids in the coarse aggregate may bear no relation to the percentage of the volume of finished concrete that is not filled by particles of coarse aggregate, because the stones are in contact in the original measurement and are pushed apart by particles of sand and films of cement paste in the concrete.

Mention of voids is made here solely to warn the inexperienced concrete user against a method which has a strong appeal because of its simplicity and apparent logic, but which is actually useless except in some special circumstances.

CHAPTER VI

SIEVE ANALYSES OF AGGREGATES

Sieves.

THE grading of aggregates, whether separate or combined, is determined by sieve analyses of representative samples. The sizes recommended for general use are those of the following British Standard sieves:

$1\frac{1}{2}$ in.
$\frac{3}{4}$ in.
$\frac{3}{8}$ in.
$\frac{3}{16}$ in.
No. 7 (aperture 0·0949 in.)
No. 14 (0·0474 in.)
No. 25 (0·0236 in.)
No. 52 (0·0116 in.)
No. 100 (0·0060 in.)

Sieves with 1-in., 2-in., and 3-in. openings are necessary for dealing with aggregates up to a maximum size of 3 in. Sieves with openings up to a maximum size of $1\frac{1}{2}$ in. should be mounted in circular brass frames, and made so as to form a nest equipped with a bottom pan and cover. A mechanical shaker is necessary when many samples have to be examined.

Sampling.

Representative samples of aggregates should be selected by the method of quartering in the following manner. Take from the pit or stock pile a sample that is as large as convenient and as representative as possible. For coarse aggregate or combined aggregate take from 50 lb. to 100 lb. Mix this thoroughly and spread it out in a layer 3 in. or 4 in. deep on a smooth floor. Divide this into quarters, and reject two opposite quarters. Remix the other two and repeat the quartering process. Repeat this until the remaining sample weighs from 3 lb. to 28 lb. in the case of coarse or combined aggregate, and from 1 lb. to 2 lb. in the case of a sand. The finer the sand the smaller the sample that is necessary. Dry the sample.

Making the Analysis.

Weigh the sample and put it into the nest of sieves arranged with the coarsest sieve on top. Shake the sieves until no more comes through any sieve. With a mechanical shaker a minimum time of fifteen to twenty minutes is necessary, depending on the proportion of fines in the sample. Weigh the residue in each sieve and the dust retained in the bottom pan. Arrange the sieve sizes and the weights of the residues as shown in the first and second columns of *Table* 3. This

shows the results of a sieve analysis of a combined gravel and sand aggregate of $\frac{3}{4}$ in. maximum size. The weight coarser than each sieve is then found by adding to the weight of the residue in each sieve the weights of the residues in all the sieves with larger openings (see the third column of the table). If the weighings and the arithmetic have been done correctly, the weight at the bottom of the third column will be equal to the weight of the sample. Next take each weight in Column 3 and express it as a percentage of the weight of the sample, getting

TABLE 3.

SIEVE ANALYSIS OF 1,000 GRAMMES SAMPLE OF $\frac{3}{4}$-IN. GRAVEL AND SAND AGGREGATE

Sieve sizes	Weight of residue in each sieve and in bottom pan (gm.)	Weight coarser than each sieve (gm.)	Percentage by weight coarser than each sieve	Percentage by weight passing each sieve
1	2	3	4	5
$\frac{3}{4}$ in.	0	0	0	100
$\frac{3}{8}$ in.	420	420	42	58
$\frac{3}{16}$ in.	205	625	62·5	37·5
No. 7	90	715	71·5	28·5
No. 14	65	780	78	22
No. 25	75	855	85·5	14·5
No. 52	85	940	94	6
No. 100	60	1,000	100	0
Pan	0	1,000	—	—
	1,000		533·5	

Fineness modulus = 533·5 ÷ 100 = 5·3 *

the figures in Column 4. These are the percentages coarser than each sieve size. Subtract each of these from 100, getting the percentage of the sample that would pass through each sieve, as given in Column 5.

Columns 1 and 5 show the result of the sieve analysis as required for ordinary purposes.

Plotting the Grading Curve.

Any ordinary squared paper may be used to plot a grading curve, the sieve sizes being set out at equal intervals. But only the sieve sizes mentioned, or another set having openings the widths of which are reduced by a constant ratio, must then be used; and interpolation for other sizes is not convenient.

The result of the sieve analysis is, however, most conveniently plotted on semi-logarithmic paper.† The logarithms of the sieve opening are plotted horizontally (or the openings themselves to a logarithmic scale), and the percentages passing the sieves are plotted vertically to a natural scale. Since each sieve opening in *Table* 3 is very nearly half of the next larger one, the logarithms of the openings differ by a nearly constant amount (log 2).

The result of the sieve analysis given in *Table* 3 is shown plotted in *Fig.* 10,

* The sum of the figures in Column 4 divided by 100 is called the "fineness modulus" of the sample. It is a convenient figure for indicating the general size of the particles in relation to the maximum size. The "fineness modulus" is low for a sample consisting mostly of fines, and high for one consisting mostly of coarse particles. It is a function of the grading, but not a description of it. It is not a description of the grading, because aggregates of the same maximum particle size may have the same fineness modulus and widely different gradings.

† Pads of semi-logarithmic paper may be obtained from firms who supply drawing office requisites.

curve No. 5. It is not necessary to plot the grading curve. Generally it is sufficient to tabulate the percentage passing each sieve opening as in *Table* 3. Only the first and last columns are required.

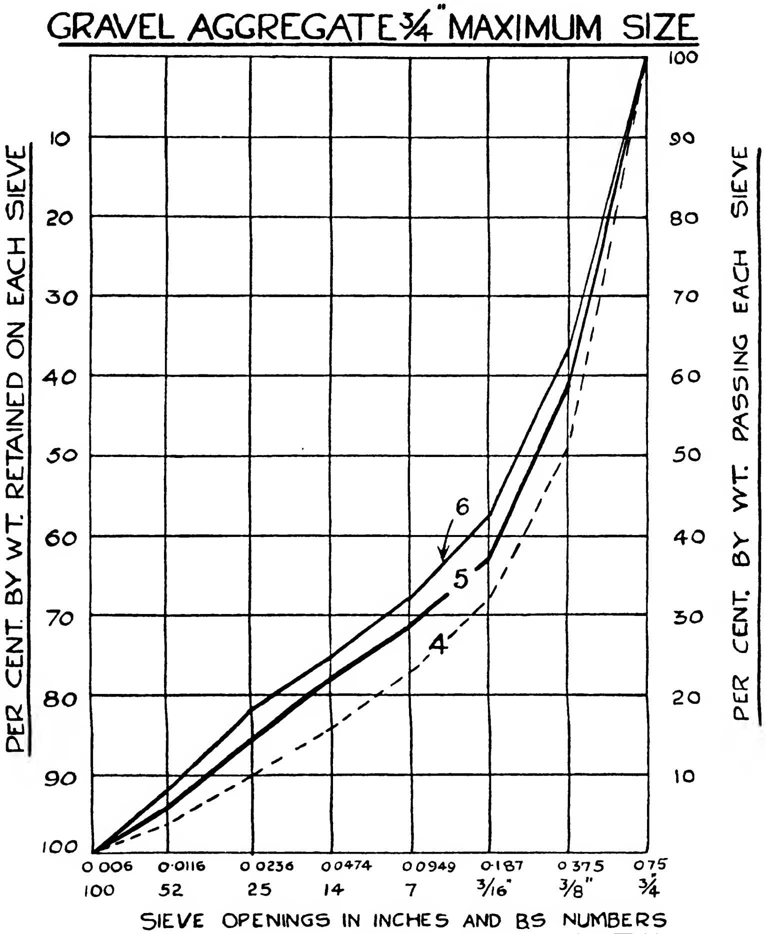


Fig. 10.—Sieve Analysis.

Comparisons of Fractions.

A picture of the grading and a direct indication of its suitability may be made in a completely different manner. The residues in the sieves are put into a series of bottles, on which marks have been placed to indicate the amount that should be in each bottle if the aggregate were suitably graded for the work in hand. These marks have been fixed previously by putting into the bottles fractions corresponding to the required grading. *Fig.* 11 is a photograph of such a set of bottles; they contain the residues from a 2-lb. sample of aggregate having

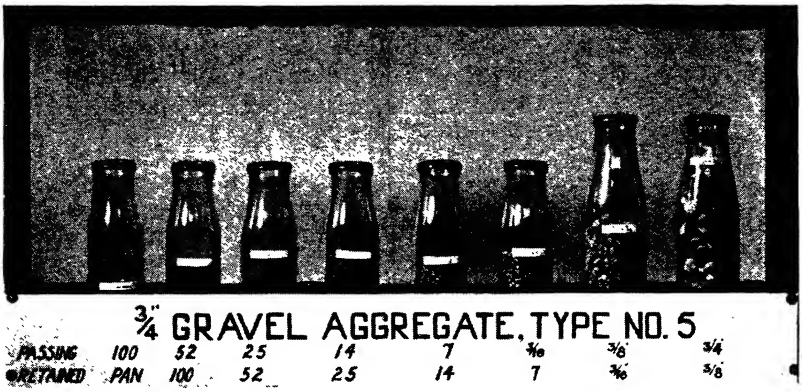


Fig. 11.—A Suitably Graded Aggregate.

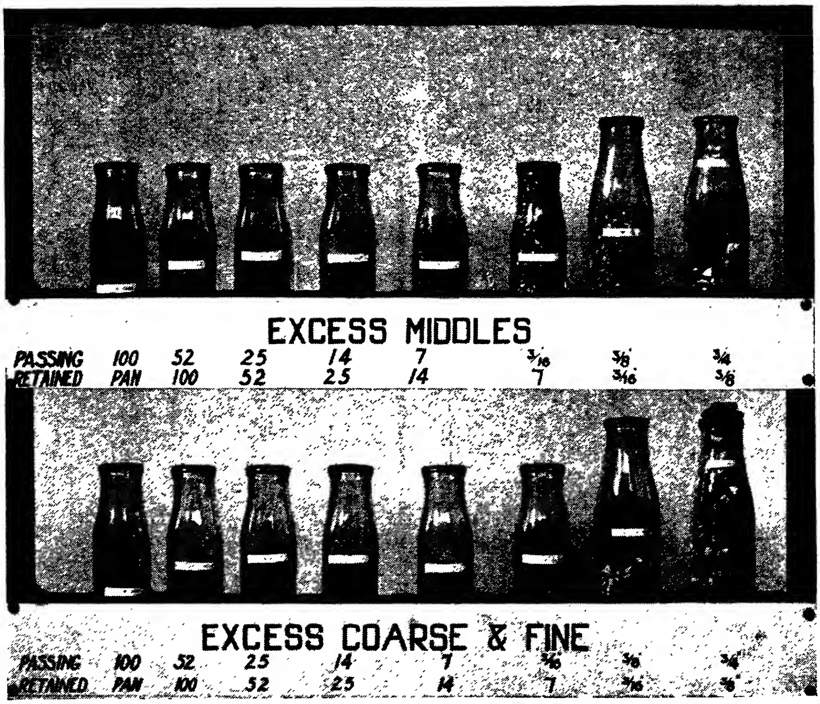


Fig. 12.—Unsuitable Gradings.

the grading shown in *Table* 3. This is a suitably graded aggregate for a certain mix.

Fig. 12 shows two sets of similar bottles containing fractions from 2-lb. samples of unsuitable aggregates. One of these has an excess of middle size particles and insufficient of the largest and smallest sizes; its grading curve would be flat at the ends and steep in the middle. The other has no particles between $\frac{3}{16}$ in. and No. 7 sieve size, and an excess of the largest and smallest sizes; its grading curve, if drawn, would be steep at each end and horizontal between the $\frac{3}{16}$-in. and No. 7 ordinates—it is a "gapped" grading.

CHAPTER VII

PRINCIPLES OF PROPORTIONING

PREVIOUS chapters deal with the materials of concrete and show how the characteristics of any given set of materials can be measured. The next step is to apply this knowledge of their characteristics in judging the merits of particular materials and, especially, in designing the proportions in which they should be used.

Arbitrary proportions and proportioning by measuring voids in the aggregates have persisted in British practice long after they have been dropped elsewhere. Arbitrary proportions (1 volume of cement : *n* volumes of sand : 2*n* volumes of coarse aggregate) give good enough results for ordinary purposes in districts where the aggregates commonly used are suitably graded (see p. 71). Elsewhere they lead to trouble unless modified. Some of the aggregates used in London and in certain other large centres are suited to 1 : 1½ : 3 and 1 : 2 : 4 proportions, mainly because the sands are fine. But there are many areas where the available sands, though not intrinsically very coarse, are coarse enough to produce harsh concretes when used in the above proportions with aggregates of ¾ in. or 1 in. maximum size.

Proportioning by Voids.—Proportioning by measuring the voids in the aggregates has nothing to recommend it except its simplicity. Possibly this simplicity and its quasi-scientific nature have caused its use to persist. The theory on which it is based is fallacious because the measured voids in the coarse aggregate are not the same as the sum of the spaces between the particles of the coarse aggregate when these are held apart by mortar in the concrete, and similarly for the sand particles coated with cement paste. The voids method may give good results if the aggregates are so graded that using this method produces dense and workable concrete. But to find out whether proposed aggregates are suitably graded for proportioning by this method sieve analyses must be made. Now, once sieve analyses have been made it is easier and more satisfactory to base proportions directly on them than to proceed more or less blindly by doubtful methods.

Proportioning by Grading and Proportion of Water to Cement.

Nearly all the methods of proportioning that have given any marked degree of satisfaction have been based directly or indirectly on sieve analyses of the aggregates combined with control of the proportion of water to cement. It will be shown later that the proportions of cement, water and aggregates, and the best grading of aggregates, for a particular set of proportions and degree of workability, are all closely inter-related. It will be shown also that these inter-relations can be made the basis of an easily understood and easily applied method of proportioning; and not only of proportioning but of maintaining control of the quality of concrete during the progress of construction.

In order to appreciate what is required in a method of proportioning and in controlling quality it is necessary to review briefly the factors upon which the quality of concrete depends. Most of these have been dealt with in detail in earlier chapters. They are summarised in the following paragraphs.

Summary of Principles.

From 75 per cent. to 85 per cent. by weight of freshly-placed concrete consists of aggregate. In a 1 : 2 : 4 concrete there are about 80 per cent. by weight of aggregate, $12\frac{1}{2}$ per cent. to $12\frac{2}{3}$ per cent. of cement, and about $7\frac{1}{2}$ per cent. of water. These proportions are liable to small variations. They indicate, however, that ordinary concrete consists mainly of aggregate.

The strength of well-compacted concrete varies directly with the ratio of the weight of cement to that of water $\left(\frac{c}{w}\right)$; that is

$$S = K\left(\frac{c}{w} - B\right)$$

where S = the strength of the concrete, say, in lb. per square inch.

$\frac{c}{w}$ = the cement-water-ratio by weight.

K = a constant (lb. per square inch) which depends on the quality of the cement, temperature and humidity conditions during maturing, and the age of the concrete.

B = a numerical constant which frequently approximates to 0·5.

To get high strength with a stated proportion of cement to aggregate it is necessary to keep the proportion of water as low as possible consistent with easy compaction of the concrete. The ease of compaction depends on the grading of the aggregate and the proportion of water. With certain gradings less water is necessary than with others. Therefore, the strength of the concrete depends indirectly on the grading of the aggregate.

Density of concrete (weight per cubic foot), which is an important index of durability, depends largely on the maximum particle size and grading of the aggregate, and partly on the proportions of cement and water used. Provided the grading of the aggregate is within certain known limits for various proportions of cement, the resulting concrete will be easily compacted without using too much water; moreover, it will be dense when compacted. Increasing the proportion of fine aggregate beyond these limits causes the use of extra water for wetting the extra sand, thereby weakening the concrete as well as reducing its density.

To make good concrete with any given proportion of cement—i.e. concrete that is easy to compact and that is dense and strong when matured—it is necessary that the grading of the aggregate and the proportion of water be within certain limits. It follows that a method of making good concrete can be based on controlling the following:

(1) The proportion of cement to combined aggregate;
(2) The grading of the combined aggregate;
(3) The proportion of cement to water; and
(4) The proportion of cement in the finished concrete, i.e. the weight of cement in a cubic yard of concrete.

All four are interdependent and can be related to the arbitrary proportions 1 : 1½ : 3, 1 : 2 : 4, etc., commonly used. Thus a 1 : 2 : 4 concrete is equivalent to proportions of 112 lb. cement to 6¼ cu. ft. of combined aggregate, requires about 7 gallons of water per 112 lb. of cement, and produces concrete containing about 505 lb. of cement per cubic yard. Since the quality of concrete depends on these four factors, and since about 80 per cent. of the concrete consists of aggregate, it follows that the making of good concrete depends to a great extent on selecting properly-graded fine and coarse aggregate, or, alternatively, on properly combining the best available aggregates. The methods described in the following chapters are based on these principles. They are easy to understand and to apply. They have been tested in practice for several years in different countries, and have been found satisfactory under widely different conditions.

Outline of Method of Proportioning.

The following is a brief outline of what is involved in using the method of proportioning. Details are given in later chapters.

(1) The grading of the combined aggregate which makes dense and workable concrete with any particular proportion of cement can be read from one of a set of diagrams of what are called type gradings (see *Figs.* 13–21). *The extent to which departures from each of these gradings are allowable without serious loss of quality in the concrete is indicated later.*

(2) The relationship between proportion of cement to combined aggregate, relative proportion of water to cement, and cement content of finished concrete for an aggregate of one of four maximum sizes can be read from the appropriate one of another set of diagrams (see *Figs.* 15–22).

(3) The proportion of cement to aggregate having been fixed from one of the diagrams mentioned in (2), or from other considerations given later (see *Table* 5), the required grading of the combined aggregate (type grading) is read from the appropriate diagram.

(4) Sieve analyses having been made, the gradings of the proposed fine and coarse aggregates are compared with the required grading of the combined aggregate (type grading). A simple arithmetical calculation shows whether the fine and coarse aggregates can be so combined as to produce a mixed (combined) aggregate having a grading agreeing closely with the type grading or lying within allowable limits.* If this can be done the aggregates are suitable, and the proportions in which they should be combined are known. If the aggregates cannot be combined so as to produce close enough agreement with the type grading, one (or both) is unsuitable and other aggregates must be sought.

(5) The weights per cubic foot loose of the fine, coarse, and combined aggregates are determined by weighing a ½-cu. ft. bucket full of each. From these the quantities of cement, sand, coarse aggregate, and water in a batch are simply calculated. The batch is usually based on 112 lb. of cement as a unit.

(6) The accuracy of the whole procedure is checked by making a small trial batch having the calculated proportions, and measuring the volume and weight of the resulting concrete, as well as noting whether it is of the required consistency and workability. The weight per cubic foot of the concrete and its cement

* A graphical method of doing this is described in some text books. The author finds the arithmetical method quicker and easier. A slide-rule is useful.

content are calculated from the measured quantities, and should agree with the expected values. Test cubes can be made from this trial batch, if desired.

Possible Variations in Gradings.

The grading diagrams *Figs.* 13–21 are for maximum sizes of aggregate from $\frac{3}{4}$ in. to 3 in. There are different diagrams for gravel and crushed stone up to $1\frac{1}{2}$ in. The diagrams for 2-in. and 3-in. maximum sizes are for crushed stone and natural sand; they can be used also for gravel of the same maximum sizes. The curves of all these diagrams are based on experiments made with gravel that was not well rounded and crushed stone containing fairly high percentages of flaky and elongated particles. While the type gradings ensure sufficient workability with poorly shaped aggregates, they give better workability with well rounded gravels and nearly cubical crushed stone. Consequently when the shape of the aggregate is really good it may be found possible to reduce the proportion of sand or, at least, to reduce the proportion of particles passing the No. 52 sieve. But this should not be done without making a trial mix to make sure that the concrete will be sufficiently workable. The degree of workability of concrete made with the type gradings is such that there is a reasonable margin of safety which allows for variations in the aggregates, accidental segregation, or slackness on the part of a workman which would tend to cause bad compaction and honeycombing. The use of less fine sand than the proportions recommended reduces this margin and greatly increases the danger of getting patches of rough, pebbly or honeycombed surfaces. There are certain other gradings, different from those in the diagrams, with which dense and workable concrete can be made, but when these are used there is more danger of segregation occurring. The best thing to do in any doubtful case is to make a trial mix.

Caution about Proportion of Water.

It has been stated that the proportion of fine sand can be reduced in certain cases. When this happens the proportion of water can be reduced also. Some of the aggregates used in the experiments from which the diagrams were derived absorbed appreciable quantities of water. With less absorbent aggregates less water may be used. For both these reasons, and because a drier consistency is better for some purposes, the proportions of water given by the various diagrams should be regarded as upper limits. Those who use the same aggregates frequently, or who are about to make large volumes of concrete with aggregates from one source, may find it worth while to make a few preliminary trial batches with different proportions of cement in order to see whether the proportion of water can be reduced. If the water proportion can be changed, it is a simple matter to draw one's own curve for proportion of water on the appropriate diagram. *In any case the proportions of water given by the various diagrams should be regarded as upper limits and used with caution.* This is important, because reduction of the proportion of water makes possible the use of a leaner mix with a corresponding saving in cost.

Interpolation.—In each of the grading diagrams five curves are drawn, one for each of the following proportions:

112 lb.	of cement	to	10	cu.	ft.	combined	aggregate	(No. 10)
112 lb.	,,	,,	8	,,	,,	,,	,,	(No. 8)
112 lb.	,,	,,	6	,,	,,	,,	,,	(No. 6)
112 lb.	,,	,,	5	,,	,,	,,	,,	(No. 5)
112 lb.	,,	,,	4	,,	,,	,,	,,	(No. 4)

The reference number of the curve is the same as the number of cubic feet of mixed (that is, combined) aggregate to be used with each 112-lb. bag of cement. It is easy to interpolate between these curves when the volume of combined aggregate to be used with one bag of cement lies between any pair of the above numbers. Very accurate interpolation is not necessary. It is even better to err slightly on the high side when workability is specially important. Thus, if $5\frac{1}{2}$ cu. ft. of aggregate are to be used per bag of cement, and if easy workability and good surface finish are very important, instead of taking a curve exactly half-way between Nos. 5 and 6 it is better to take one slightly nearer to No. 6, especially on the sand side of the separating size.

Degree of Accuracy.—It is not necessary to be extremely accurate in the arithmetical calculations referred to in (4) on p. 40. The nearest 0·5 per cent. or even 1 per cent. is good enough in most cases. Neither is very close agreement necessary between the grading curve of the actual mixed aggregate and the type curve; but it is better to have the left-hand, or sand, part of the curve for the actual aggregate slightly higher than the type curve in all cases where easy workability is specially important, as in heavily reinforced beams and columns. Some of the examples worked out in later chapters show remarkably close agreement between the actual gradings and the type grading; such close agreement has been common in the author's experience. However, it cannot be expected in every case.

The directions given in later chapters will show how to decide in doubtful cases in which the divergence between the two gradings begins to be serious. In the last resort one can decide by making a trial mix and, judging by the consistency, workability, and weight per cubic foot of the fresh concrete, and, if necessary, by the strengths of test cubes, decide whether the concrete will be good enough for the work in hand.

Checking by Trial Mix.—A trial mix is always advisable and frequently necessary. It must be made when differences between the grading of the actual aggregate and the type grading are great enough to raise doubts about the probable quality of the concrete. Apart from this it is always advisable to make a trial mix with unfamiliar aggregates. Aggregates differ so much in their power of absorbing water that one can be sure of the proportion of water only when using aggregates of which one has had previous experience.

It is not necessary to use elaborate methods of calculating the proportion of water, especially methods which involve determining absorption of water by the aggregates. A trial mix made with a batch containing as little as 10 lb. to 20 lb. of cement gives valuable indications of all the qualities of the concrete, and shows whether the proportion of water is correct. It is quicker and easier to base the final proportion of water on such a trial mix than to measure and allow for absorption.

Moreover, the trial mix is a check on all that has been done, including the arithmetic, as any serious errors will be revealed by some property of the concrete

being different from that expected. The only equipment necessary is weighing apparatus, a steel or iron plate (or other non-absorbent material) on which to do the mixing, a cylindrical bucket of exactly a half cubic foot capacity, and shovels and trowels. The work is greatly facilitated by eliminating ounces from the weighing. Special small weights of 0·1 lb., 0·05 lb., and 0·01 lb. can be easily and cheaply made in brass. They enable all weighings to be put on a decimal basis.

Details of the method outlined above will be elaborated in subsequent chapters.

CHAPTER VIII

TYPE GRADINGS FOR $\frac{3}{4}$-IN. AGGREGATES

Grading for Density and Workability.—A combined aggregate must be suitably graded from the largest to the smallest particles in order that the concrete made with it may be both workable and dense. The suitability of the grading depends on the following factors:

(1) The proportion of cement to aggregate,
(2) The size of the largest particles of the aggregate, and
(3) The shape of the particles.

Grading in Relation to Proportions.—In general, and within limits, the smaller the proportion of fines and middle sizes in the dry mixture of cement and aggregate the denser the concrete. In a $\frac{3}{4}$-in. aggregate the particles passing the No. 14 sieve may be classed as fines; particles between the No. 14 sieve and $\frac{3}{8}$ in. may be regarded as middle sizes. For workability fines are necessary. Within limits the higher the proportion of fines the greater the workability. For maximum density the fines and middles should be reduced; for workability the fines should be increased. These opposite demands of density and workability can be balanced, so as to produce a suitable type of dry mixture, by adjusting the proportion of fines to meet both as nearly as possible. A small addition of fines and middle sizes to the grading for maximum density makes only a slight reduction in density, but such an addition greatly increases the workability. It is possible to adjust the grading for a particular mix so that the density of the resulting concrete is not seriously reduced and yet the workability is increased sufficiently to allow easy placing by ordinary methods. By so balancing the conflicting demands of density and workability a grading suitable for making dense and workable concrete is obtained. When the proper proportion of water is mixed with this the resulting concrete is sufficiently workable to be placed between and around the reinforcement, and at the same time its density is not much less than the maximum attainable.

In the dry mix of cement and aggregate the fines consist of the cement and the smallest particles of aggregate. If the cement is reduced the proportion of the smallest particles of aggregate must be increased and vice versa. It follows, on considering the aggregates alone, that for rich mixes the combined aggregate should contain a low proportion of small particles, and for lean mixes it should contain a much higher proportion of fines.

Effect of Maximum Particle Size.—For the same proportion of cement to combined aggregate and the same general shape of particle, the proportion of fine aggregate may be decreased as the maximum particle size is increased without sacrificing workability. That is, less sand and more coarse aggregate may be used.

Effect of Shape of Particle.—The extremes of shape occur in well-rounded gravel particles and crushed stone that is sharply angular rather than cubical. Crushed stone requires more fines than gravel for equal workability with the same proportion of cement and the same maximum size. Therefore, for the same maximum particle size and the same proportion of cement, the grading of a combined aggregate consisting wholly of crushed stone, or crushed stone and sand, is different from that of a gravel aggregate which gives the same workability.

Type Grading.—The grading of a combined aggregate of a particular maximum size that produces dense and workable concrete with a stated proportion of cement is called the *type grading* for that proportion of cement and maximum size of particle.

Curve No. 5 (*Fig.* 10) shows the grading of a $\frac{3}{4}$-in. gravel aggregate suitable for making dense and workable concrete in a mix proportioned with 112 lb. of cement to 5 cu. ft. of DRY combined aggregate. It is suitable in the sense that when used in the proportion stated it makes concrete that is both dense and workable. An aggregate represented by a *lower curve* such as No. 4 (that is, one containing more coarse particles and less fines), when used with the same proportion of cement, would make harsher concrete that would be more difficult to place. If satisfactorily placed, the concrete would be denser. An aggregate represented by a *higher curve* than No. 5, say No. 6 (that is, one containing less large and more small particles), when used with the same proportion of cement, would make a more workable concrete provided a little extra water were added. But this concrete would be neither so strong nor so dense as concrete made with aggregates graded according to curve No. 5. In curve No. 5 the opposing demands of density for decreased fines and of workability for increased fines are balanced. It is the type curve, representing the type grading, for proportions of 112 lb. of cement to 5 cu. ft. of dry combined $\frac{3}{4}$-in. gravel aggregate.

Other proportions of cement to aggregate require other gradings. Thus curve No. 6 of *Fig.* 10 is the type curve for a mix of 112 lb. of cement to 6 cu. ft. of dry combined aggregate ($\frac{3}{4}$-in. gravel), and curve No. 4 of *Fig.* 10 is the type curve for a mix of 112 lb. of cement to 4 cu. ft. of dry combined aggregate ($\frac{3}{4}$-in. gravel).

Latitude.—When a mix is made with 112 lb. of cement and 5 cu. ft. of a gravel having a grading represented by a curve above No. 5, the concrete is more workable but less dense than when the aggregate is graded to curve No. 5. This assumes that a suitable proportion of water is used. If the grading curve of the aggregate is much higher than that indicated by curve No. 5 the loss in density is serious. However, if the grading curve of the aggregate lies within the zone between curves Nos. 5 and 6, the loss of density is small enough to be negligible for ordinary purposes. Even if the aggregate grading curve lies slightly above curve No. 6 the loss of density is not great. Also, if the aggregate contains a little more coarse particles, less middle-size particles, and more fines than the type grading, so long as the aggregate grading curve is approximately averaged by curve No. 5, the concrete still remains workable and the loss of density is not great. Consequently it is not necessary that the actual aggregate grading should coincide with the type grading. Some latitude is allowable. Its extent is indicated by the zone between curves Nos. 5 and 6.

GRAVEL AGGREGATE : ¾" MAXIMUM SIZE

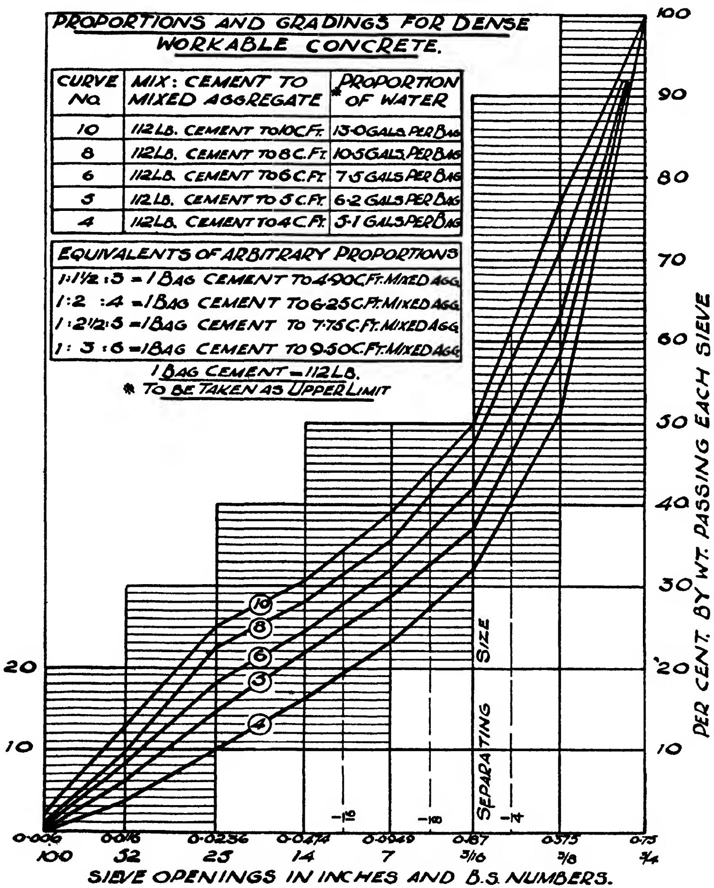


Fig. 13.

CRUSHED STONE AGGREGATE : ¾" MAXIMUM SIZE

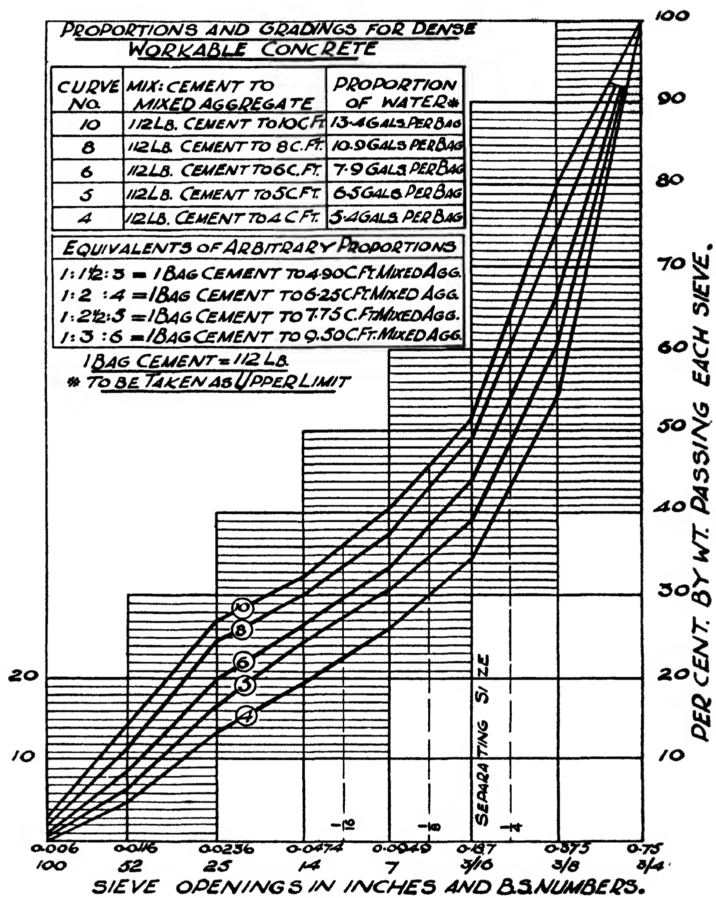


Fig. 14.

In a mix of 112 lb. of cement to 5 cu. ft. of aggregate any gradings below curve No. 5 lead to harshness and difficulty in placing, characteristics which should be avoided in reinforced concrete work. For the same proportions density begins to fall off rapidly with aggregates represented by grading curves lying much above curve No. 6. Any aggregate having a grading curve which lies wholly in the zone between curves Nos. 5 and 6 (and which follows the trend of the zone boundaries) makes excellent concrete when mixed in the proportion of 112 lb. of cement to 5 cu. ft. of *dry* combined aggregate.

Effects of Departures from the Type Gradings.—The effects on the resulting concrete of using aggregates other than those of the type gradings may be summarised as follows:

(1) Aggregates coarser than the type grading for any mix (that is, where the aggregate grading curve lies below the type curve) make harsh concretes;

(2) Aggregates much finer than the type grading (grading curve of aggregates lying well above the type curve) make workable concretes of relatively low density and strength;

(3) Excess middles cause harshness and honeycombing;

(4) Lack of middles and excess of fines cause "fatness" or very easy workability at the expense of density and strength; and

(5) When the coarse aggregate is all close to the maximum size and the sand part of the actual grading follows the type curve, the concrete is usually workable and dense but liable to segregation.

¾-in. Gravel Aggregates.—*Fig.* 13 contains a set of type gradings for ¾-in. gravel aggregates and proportions of 112 lb. of cement to 4, 5, 6, 8, and 10 cu. ft. of combined aggregate respectively. The number on each curve indicates the number of cubic feet of *dry* combined aggregate of that grading to be used with 112 lb. of cement. All volumes of aggregate are loose volumes as already described.

What has been said previously about the zone 5–6 in relation to a mix of 112 lb. of cement to 5 cu. ft. of aggregate applies also to each of the other zones in relation to the mix specified for the lower boundary of the zone. Thus, any aggregate represented by a curve lying in the zone 6–8 will make excellent concrete in the proportions 112 lb. of cement to 6 cu. ft. of combined aggregate.

The gradings represented by these curves are tabulated in the upper part of *Table* 4.

¾-in. Crushed Stone.—Type gradings for ¾-in. crushed stone are given in *Fig.* 14 and in the lower part of *Table* 4.

Proportions of Water and Cement Contents with ¾-in. Aggregates.

Table 4 also contains recommendations for the proportions of water to be used in the various mixes. *Since the proportion of water to cement necessary to produce a given consistency varies with the absorption of the aggregates, the recommended values should be used with caution.** *It is advisable to make a trial batch of*

* See Chapter VII, p. 41.

TABLE 4.—TYPE GRADINGS FOR VARIOUS PROPORTIONS FOR AGGREGATES OF ¾-IN. MAXIMUM SIZE.

Reference number	Mix (number of cu. ft. of dry combined aggregate to 112 lb. cement)	Sieve Sizes								Approximate proportions of water to cement in gallons per 112 lb. of cement for easy workability *	Kind of aggregate
		No. 100 (0·0060 in.)	No. 52 (0·0116 in.)	No. 25 (0·0236 in.)	No. 14 (0·0474 in.)	No. 7 (0·0949 in.)	3/16 in. (0·187 in.)	⅜ in. (0·375 in.)	¾ in. (0·75 in.)		
		A. Percentage by Weight Passing each Sieve (Gravel and Sand Aggregates)									
10	10	2·0	12·5	25	30·5	39	50	77	100	13·0	¾-in. gravel and sand
8	8	1·0	9·5	22·5	28	35·5	48	71	100	10·5	
6	6	0·5	8	18	24·5	32	42	63	100	7·5	
5	5	0	6	14·5	22	28·5	37	58	100	6·2	
4	4	0	3·5	10	16	23	32	51	100	5·1	
	Equivalent to 1 : 2 : 4 } 6·3	0·6	8·3	19·5	25	32·5	43·5	65	100	8·4	
	Equivalent to 1 : 1½ : 3 } 4·9	0	6	14	21	27·5	36·5	57	100	6·1 *	
		B. Crushed Stone Aggregates									
10	10	3	14·5	27	32·5	40·5	51·5	80	100	13·4	¾-in. crushed stone
8	8	2	11·5	24·5	30	37·5	49	74	100	10·9	
6	6	1·0	8·5	20	26·5	33·5	44	66·5	100	7·9	
5	5	0·5	6·5	16·5	24·5	30·5	39	60·5	100	6·5	
4	4	0	5·0	13·5	19·5	26	34·5	54·5	100	5·4	
	Equivalent to 1 : 2 : 4 } 6·3	1·1	9·5	21·5	27·5	34·5	45·5	69	100	8·6	
	Equivalent to 1 : 1½ : 3 } 4·9	0·5	6·5	16·5	24	30	38·5	60	100	6·4 *	

* All the figures given for water proportions should be regarded as upper limits. Start with less water in a trial batch and work up to the required consistency.

concrete, using less water than the proportion recommended, and to add water until the required consistency is attained.

Fig. 15 is supplementary to *Table* 4 and to *Figs.* 13 and 14. It shows the cement-water-ratios by weight and the proportions of water in gallons per bag used by the author in the experimental work on which *Table* 4 is based. It also contains curves showing the cement content per cubic yard of concrete to be expected in concretes made with the type gradings and proportions of cement to aggregate shown on the diagrams.

Variations of $\pm$ 4 per cent. from the values given by the cement-content curves may be expected in practice due to differences in methods of filling aggregates into measures and to the effects of small variations from the type gradings. The curve labelled crushed stone is for crushed stone combined with crusher dust. When crushed stone is used with natural sand, values intermediate between the two curves and closer to the gravel curve should be used.

Uses of Table 4 and Fig. 15.—A few examples will serve to show the uses of *Table* 4 and *Fig.* 15.

> EXAMPLE 1.—A concrete is to be made in the proportions of 112 lb. of cement to $4\frac{1}{2}$ cu. ft. of combined aggregate consisting of $\frac{3}{4}$-in. gravel and natural sand. What should be the grading of the combined aggregate, the proportion of water in gallons per bag, the cement-water-ratio, and the cement content of the concrete?

The grading is found from the upper part of *Table* 4 by interpolating between the gradings numbered 4 and 5, with the following result (the interpolation is made to the nearest 0·5 per cent.):

Sieve sizes	100	52	25	14	7	$\frac{3}{16}$ in.	$\frac{3}{8}$ in.	$\frac{3}{4}$ in.
Percentage passing . .	0	5	12	18·5	25·5	34·5	54·5	100

The quantity of water is found from the lower water proportion curve in *Fig.* 15. The ordinate of the curve corresponding to $N = 4\frac{1}{2}$ is 5·7 gallons per 112-lb. bag. The cement-water-ratio is read from the upper part of the diagram and is 2·0. The cement content, read from the appropriate curve, is 680 lb. per cubic yard of concrete.

> EXAMPLE 2.—Concrete is to be made with $\frac{3}{4}$-in. crushed stone and the cement content is to be 550 lb. per cubic yard of concrete. Find the proportion of cement to combined aggregate, the grading of the aggregate, and the proportion of water.

The proportion of cement to aggregate is got from *Fig.* 15 by finding the value of N corresponding to the point in which the cement-content curve for crushed stone cuts the horizontal line representing 550 lb. of cement per cubic yard. N is found to be very nearly 6 (actually it is 5·95). Consequently for a first approximation a mix of 1 bag (112 lb.) to 6 cu. ft. of dry combined aggregate may be tried. The grading is that numbered 6 in part *B* of *Table* 4.

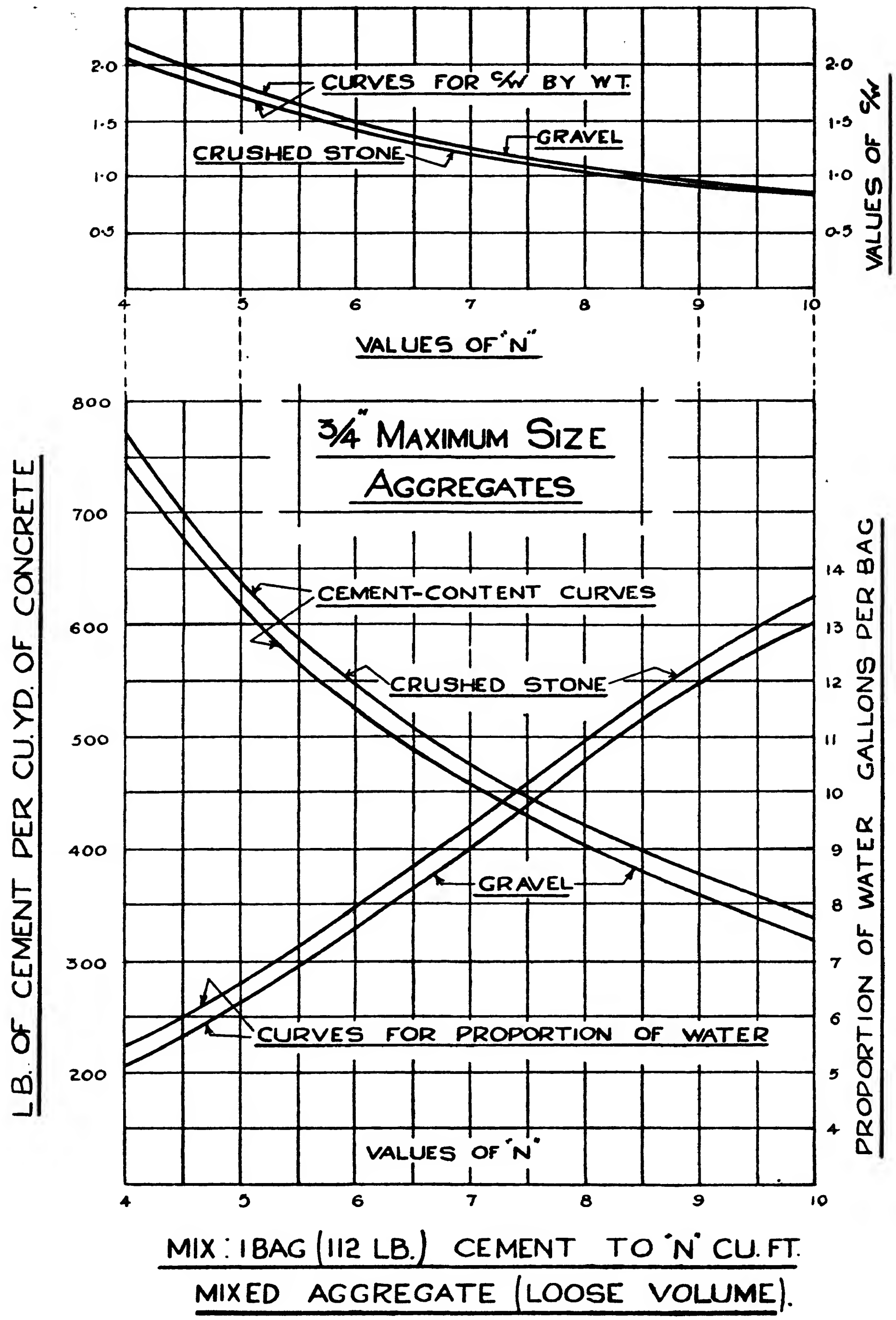

CURVES FOR C/W BY WT.
GRAVEL
CRUSHED STONE
VALUES OF C/W
2·0
1·5
1·0
0·5
VALUES OF "N"
3/4" MAXIMUM SIZE AGGREGATES
CEMENT-CONTENT CURVES
CRUSHED STONE
GRAVEL
CURVES FOR PROPORTION OF WATER
LB. OF CEMENT PER CU. YD. OF CONCRETE
800
700
600
500
400
300
200
PROPORTION OF WATER GALLONS PER BAG
14
13
12
11
10
9
8
7
6
5
4
VALUES OF "N"
4
5
6
7
8
9
10
MIX: 1 BAG (112 LB.) CEMENT TO "N" CU. FT.
MIXED AGGREGATE (LOOSE VOLUME).

Fig. 15.

The proportion of water is read from the upper water proportion curve, and is slightly less than 8 gallons per bag.

EXAMPLE 3.—Concrete of a certain strength is required and preliminary tests have shown that $\frac{c}{w}$ should be equal to 1·5. Find the proportions and suitable gradings for the fine and coarse aggregates. The aggregate is to be $\frac{3}{4}$-in. crushed stone.

The $\frac{c}{w}$ curve for $\frac{3}{4}$-in. crushed stone shows that $N = 5{\cdot}6$. The proportions are therefore 1 bag of cement to 5·6 cu. ft. of *dry* combined aggregate.

The grading of the aggregate is got by interpolating between numbers 5 and 6 in the lower part of *Table* 4, thus:

Sieves	100	52	25	14	7	$\frac{3}{16}$ in.	$\frac{3}{8}$ in.	$\frac{3}{4}$ in.
Percentage passing	0·8	7·7	18·6	25·7	32·3	42	64	100

Since the required cement-water-ratio is 1·5, the proportion of water is $(11{\cdot}2 \times \frac{2}{3}) = 7{\cdot}47$ gallons per bag.

Proportions of Cement, Fine Aggregate, and Coarse Aggregate.

So far only the proportions of cement to combined aggregate have been found. The proportions of cement to fine and to coarse aggregate have yet to be found. In most cases the weight per cubic foot (loose) of dry combined aggregates of the type gradings for the richer mixes is not far from 112 lb. per cubic foot. As a first approximation, therefore, the weight of aggregates per 112 lb. of cement is $112 \times 5{\cdot}6 = 627$ lb. All the fine aggregate is to pass a $\frac{3}{16}$-in. sieve. The grading shows that 42 per cent. of the aggregate should pass a $\frac{3}{16}$-in. sieve, therefore the first approximation to the weight of fine aggregate is $627 \times \frac{42}{100} = 263$ lb. and the weight of coarse aggregate is $627 \times \frac{58}{100} = 364$ lb. Final proportions cannot be fixed until the aggregates proposed for use have been examined.

Grading of Fine Aggregate.—Further, the proper grading for the fine aggregate can be found. 100 lb. of aggregate of the required grading contains 42 lb. of fine aggregate. Of this, 0·8 per cent. should pass the No. 100 sieve. That is, $\frac{0{\cdot}8}{42} \times 100 = 1{\cdot}9$ per cent. should pass the No. 100 sieve. Similarly $\frac{7{\cdot}7 \times 100}{42} = 18{\cdot}3$ per cent. should pass the No. 52 sieve, and so on. The grading of the fine aggregate is so found to be as follows:

Sieves	100	52	25	14	7	$\frac{3}{16}$ in.
Percentage passing	1·9	18·3	44	61	77	100

Grading of Coarse Aggregate.—The grading of the coarse aggregate can also be found. From the grading of the combined aggregate it can be seen that since 42 per cent. must pass the $\frac{3}{16}$-in. sieve, 58 per cent. must be coarser than this size. That is, a sample of 100 lb. contains 58 lb. of coarse aggregate. Also the percentage passing the $\frac{3}{8}$-in. sieve and retained on the $\frac{3}{16}$-in. sieve is $64 - 42 = 22$ lb., or 22 lb. out of the 58 lb. (38 per cent.) of coarse aggregate should pass the $\frac{3}{8}$-in. sieve. Therefore the grading of the coarse aggregate should be:

Sieves	$\frac{3}{16}$ in.	$\frac{3}{8}$ in.	$\frac{3}{4}$ in.
Percentage passing	0	38	100

One more example will illustrate another use of *Table* 4 and *Fig.* 15.

EXAMPLE 4.—The concrete of Example 3 is to be made, and a sample of sand and a sample of crushed stone have been submitted. They are to be tested for suitability. If they are suitable, the proportions in which they are to be used are required.

Their gradings are found on sieving to be as follows:

Sieves	100	52	25	14	7	$\frac{3}{16}$ in.	$\frac{3}{8}$ in.	$\frac{3}{4}$ in.
Percentage passing:								
Sand	1·5	20	42	62	75	96	100	100
Crushed stone	0	0	0	0·5	2	4·3	40	100

The sand weighed 107 lb. per cubic foot when dry (loose volume). The crushed stone weighed 89 lb. per cubic foot when dry (loose volume). The sand weighed 81·5 lb. per cubic foot when containing 4 per cent. of moisture (loose volume).

Direct comparison of these gradings with those worked out as suitable in Example 3 shows that each material is suitable.

The next step is to determine the proportion of fine aggregate to coarse aggregate. Reference to the type grading for the combined aggregate shows that 42 per cent. must pass the $\frac{3}{16}$-in. sieve.

If the whole of the fine aggregate passed a $\frac{3}{16}$-in. sieve and if the whole of the coarse aggregate were retained on it, then the obvious proportions by weight would be 42 per cent. of fine to 58 per cent. of coarse. In this case only 96 per cent. of the fine aggregate passes the $\frac{3}{16}$-in. sieve, but 4·3 per cent. of the coarse aggregate also passes it. We may, therefore, still use the proportions 42 to 58. Then, since the aggregates are more or less correctly graded, if we get the right percentage passing the $\frac{3}{16}$-in. sieve, we should have nearly the right percentage passing each of the other sieves. We, therefore, make a calculation to determine the effect of mixing 42 lb. of fine aggregate with 58 lb. of coarse aggregate.

The calculation may be set out as follows:

Sieves	100	52	25	14	7	$\frac{3}{16}$ in.	⅜ in.	¾ in.
Weight passing each sieve out of 42 lb. of sand	0·6	8·4	17·6	26	31·5	40·3	42	42
Weight passing each sieve out of 58 lb. of crushed stone	0	0	0	0·3	1·2	2·5	23·2	58
Weight passing each sieve out of 100 lb. of combined aggregate	0·6	8·4	17·6	26·3	32·7	42·8	65·2	100
Type grading from Example 3	0·8	8	18·5	25·5	32·5	42	64	100

The agreement is close enough. The combined aggregate contains less passing the No. 100 and No. 25 sieves than the type grading, but more passing the Nos. 52, 14, 7 and the $\frac{3}{16}$-in. sieves. Therefore the sand and crushed stone may be combined in the proportions of 42 to 58 by weight (dry).

The combined aggregate resulting from mixing these proportions weighed 114 lb. per cubic foot when dry (loose volume) and 102 lb. per cubic foot when moist (loose volume). Since the proportions found in Example 3 were 112 lb. of cement to 5·6 cu. ft. of dry combined aggregate, we require $5{\cdot}6 \times 114 = 638$ lb. of dry aggregate. 42 per cent. of this, or 268 lb., is to be sand, and 58 per cent., or 370 lb., is to be stone.

Proportions.—The proportion of cement to sand to stone is

112 lb. of cement : 268 lb. of dry sand : 370 lb. of crushed stone,

or, dividing by the proper weights per cubic foot of sand and stone,

112 lb. of cement : 2·5 cu. ft. of *dry* sand : 4·15 cu. ft. of crushed stone,

or,

112 lb. of cement : 3·3 cu. ft. of *moist* sand : 4·15 cu. ft. of crushed stone,

or approximately

112 lb. of cement : 3⅓ cu. ft. of *moist* sand : 4⅛ cu. ft. of crushed stone.

Water.—7·46 gallons per bag for dry aggregates, with a reduction in the case of moist aggregates equal to the volume of water carried by the 3·3 cu. ft. of sand and 4·15 cu. ft. of stone.

The amount of cement required will be about 580 lb. per cubic yard of concrete.

Trial Mix.—A trial mix of these proportions but with an actual cement-water-ratio of 1·49, which is 7½ gallons per bag, made easily workable concrete. It weighed 148·4 lb. per cubic foot.

These examples show how *Figs.* 13 and 14 or *Table* 4 may be used in conjunction with *Fig.* 15 for deciding whether aggregates are suitably graded and for designing the proportions of mixes. The diagrams to be given subsequently for aggregates of other maximum sizes may be used similarly.

CHAPTER IX

TYPE GRADINGS FOR $1\frac{1}{2}$-IN. AGGREGATES

$1\frac{1}{2}$-in. Gravel Aggregates.—*Fig.* 16 contains a set of type curves for gravel aggregates of $1\frac{1}{2}$-in. maximum size. They are arranged similarly to those of *Fig.* 13 and their uses are similar. Concrete made with aggregates of these gradings and the specified proportions of cement and water has about the same workability as corresponding concrete made with $\frac{3}{4}$-in. gravel aggregates of the type gradings.

$1\frac{1}{2}$-in. Crushed Stone Aggregates.—*Fig.* 17 is the corresponding diagram for crushed stone. The general nature of the workability is again the same.

Water Proportions and Cement Contents.—*Fig.* 18 contains proportions of water for various proportions of aggregate to cement for $1\frac{1}{2}$-in. aggregates and cement contents of the resulting concretes. It corresponds to *Fig.* 15, and can be used in the same way.

The curves for cement content and proportion of water marked "crushed stone" of *Figs.* 15 and 18 were prepared for combinations of crushed stone and crusher fines or "stone-sand." For the more usual combinations of crushed stone and natural sand, points intermediate between the crushed stone and gravel curves and close to the latter should be taken. The type gradings for crushed stone aggregates are independent of the nature of the fine aggregate.

$1\frac{1}{2}$-in. Aggregates require Less Water than $\frac{3}{4}$-in. Aggregates.—Comparison of *Figs.* 15 and 18 shows that the proportions of water are lower for concretes of the same proportions of cement to aggregate made with $1\frac{1}{2}$-in. aggregates than for those made with $\frac{3}{4}$-in. aggregates, other things being equal. This is so because the $1\frac{1}{2}$-in. type gradings contain smaller proportions of fines and smaller surface areas to be wetted than the corresponding $\frac{3}{4}$-in. type gradings.

Less Sand with $1\frac{1}{2}$-in. than with $\frac{3}{4}$-in. Aggregates.—Comparison of corresponding type curves shows that curves bearing the same numbers on *Figs.* 13 and 16 intersect the $\frac{3}{16}$-in. ordinate at lower points on *Fig.* 16 than on *Fig.* 13. Similarly the curves on *Fig.* 17 intersect the $\frac{3}{16}$-in. ordinate at lower points than the corresponding curves on *Fig.* 14. This means that less sand is necessary with $1\frac{1}{2}$-in. aggregates than with $\frac{3}{4}$-in. aggregates of the same kind for the same proportion of cement and the same degree of workability.

Diagrams for $1\frac{1}{2}$-in. Aggregates used like those for $\frac{3}{4}$-in. Aggregates.—The diagrams for $1\frac{1}{2}$-in. aggregates are used in the same manner as those for $\frac{3}{4}$-in. aggregates. The following example illustrates this.

> Example 5.—A 1 : 2 : 4 concrete is to be made with a gravel screened between $1\frac{1}{2}$ in. and $\frac{3}{16}$ in., and a sand screened through a $\frac{3}{16}$-in. screen. Assuming clean separation, what should be the grading of the gravel and the grading of the sand?

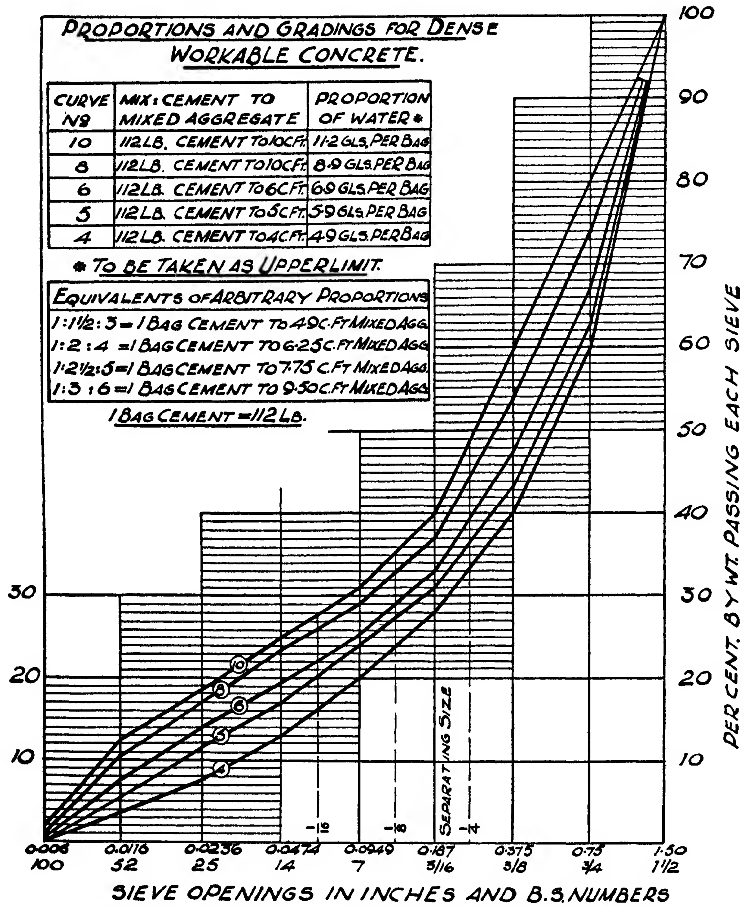


Fig. 16.—Gravel aggregate: 1½-in. maximum size.

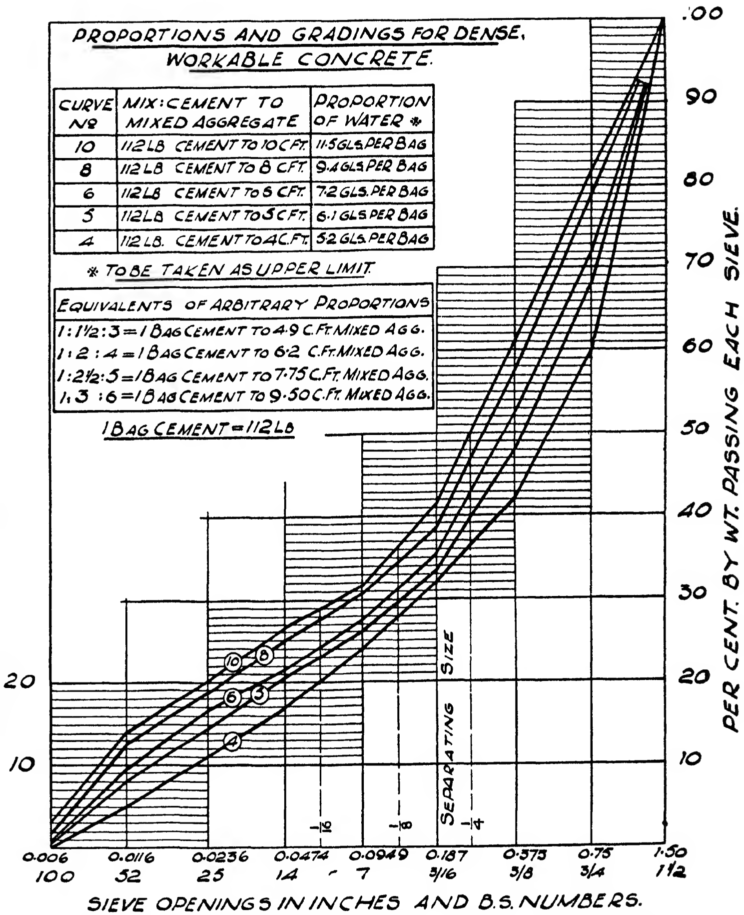


Fig. 17.—Crushed stone aggregate: 1½-in. maximum size.

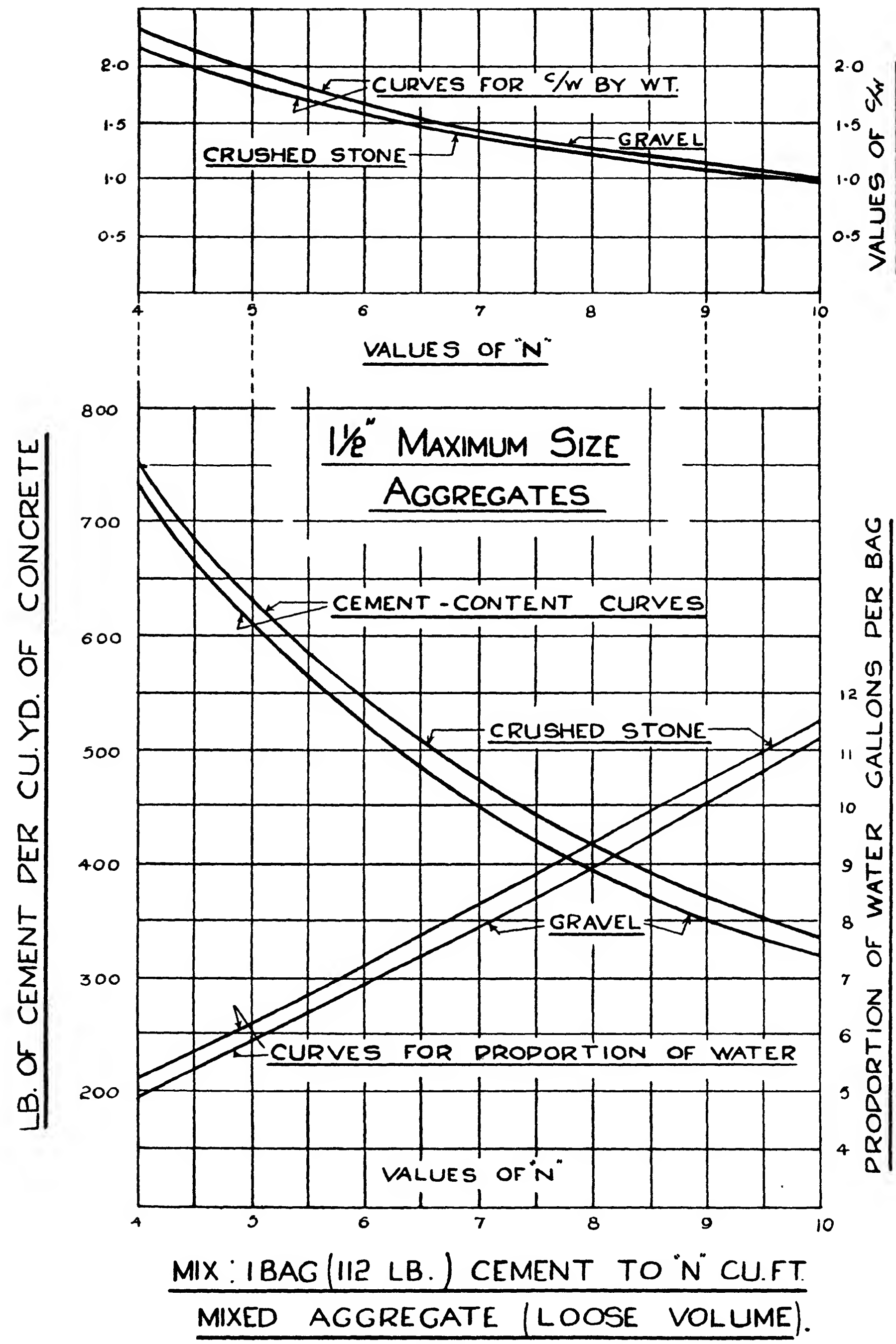

CURVES FOR C/W BY WT.
GRAVEL
CRUSHED STONE
VALUES OF C/W
2·0
1·5
1·0
0·5
4
5
6
7
8
9
10
VALUES OF "N"
1½" MAXIMUM SIZE AGGREGATES
CEMENT-CONTENT CURVES
CRUSHED STONE
GRAVEL
CURVES FOR PROPORTION OF WATER
LB. OF CEMENT PER CU. YD. OF CONCRETE
800
700
600
500
400
300
200
PROPORTION OF WATER GALLONS PER BAG
12
11
10
9
8
7
6
5
4
VALUES OF "N"
MIX: 1 BAG (112 LB.) CEMENT TO "N" CU. FT. MIXED AGGREGATE (LOOSE VOLUME).

Fig. 18.

Usually when the proportion of gravel is twice that of sand, and the specific gravities of both materials are the same, the proportions by weight are close to 65 to 35; that is, 65 per cent. of gravel to 35 per cent. of sand. Therefore the grading curve for the mixed aggregate must pass through the 35-per cent. point on the separating ordinate to satisfy the requirement of 2 to 1 proportions of gravel and sand.

The equivalent of a 1 : 2 : 4 concrete is 112 lb. of cement to 6¼ cu. ft. of combined aggregate. By interpolating on *Fig.* 16 we find the type grading for 112 lb. of cement to 6¼ cu. ft. of combined aggregate to be *A* in the table. But in order to have 35 per cent. passing the $\frac{3}{16}$-in. sieve this must be altered to the grading *B*.

Sieves	100	52	25	14	7	$\frac{3}{16}$ in.	$\frac{3}{8}$ in.	$\frac{3}{4}$ in.	1½ in.
A. Type: Percentage passing	0·6	8·2	14·8	20·5	26·4	**34**	49	68·8	100
B. Modified type: Percentage passing	0·6	8·2	14·8	20·5	26·4	**35**	49	68·8	100
C. Sand: Percentage passing	1·7	23·4	42·3	58·6	75·5	100	—	—	—
D. Gravel: Percentage passing	—	—	—	—	—	0	21·5	52	100

B, then, is the grading we want in the combined aggregate. This contains 35 lb. of sand in 100 lb. of mixed aggregate; of this 26·4 lb. pass the No. 7 sieve, 20·5 lb. pass the No. 14, and so on. The grading of the sand is found by dividing these figures by 35 and multiplying by 100. The result is given in line *C*.

There are 65 lb. of gravel in 100 lb. of the mixed aggregate. Of this $49 - 35 = 14$ lb. are smaller than $\frac{3}{8}$ in., and $68{\cdot}8 - 35 = 33{\cdot}8$ lb. are smaller than $\frac{3}{4}$ in. The grading of the gravel alone is found by dividing each of these weights by 65 and multiplying by 100, and is given in line *D*.

The separate gradings of sand and coarse aggregate for any other condition or maximum size may be found by calculations similar to those worked out in this example.

> EXAMPLE 6.—A crushed stone and a natural sand are to be used in a mix of 112 lb. of cement to 5 cu. ft. of dry combined aggregate. The crushed stone is nominally 1½ in. to $\frac{3}{16}$ in. but contains some material finer than $\frac{3}{16}$ in., as shown in the table. What is the best sand grading to use with this stone?

Line *A* of the table below gives the type grading for 1 bag of cement to 5 cu. ft. of 1½-in. crushed stone (see *Fig.* 17).

Sieves	100	52	25	14	7	$\frac{3}{16}$ in.	$\frac{3}{8}$ in.	$\frac{3}{4}$ in.	1½ in.
A. Type grading	0·5	8	14·5	20·5	26	33·5	48	68	100
B. Stone grading	0	0	0	0	2	9	30	60	100
C. From 66·5 lb. of stone	0	0	0	0	1·3	6	20	40	66·5
D. From 73 lb. of stone	0	0	0	0	1·5	6·6	21·9	43·8	73
E. From 27 lb. of sand	0·5	8	14·5	20·5	24·5	27	27	27	27
$F = D + E$	0·5	8	14·5	20·5	26	33·6	48·9	70·8	100
G. Sand grading	1·9	29·6	53·7	76	90·6	100	—	—	—

The type grading shows that the 100 lb. of mixed aggregate is to consist of 33·5 lb. finer than $\frac{3}{16}$ in. and 66·5 lb. coarser than $\frac{3}{16}$ in. But if 66·5 lb. of this stone were mixed with 33·5 of sand finer than $\frac{3}{16}$ in., the mixture would contain 39·5 lb. out of 100 lb. finer than $\frac{3}{16}$ in., whereas the type grading requires only 33·5 per cent. passing the $\frac{3}{16}$-in. sieve. Hence some other proportion of stone to sand should be used.

What has to be done is to determine the weights of stone and sand, between them totalling 100 lb., which will have 33·5 lb. finer than $\frac{3}{16}$ in. This can be done most readily by trial.

The amount of sand must be about 27 lb., because the stone will contain between 6 lb. and 7 lb. finer than $\frac{3}{16}$ in. By trying 73 lb. (100 — 27) of stone we get line *D*, which gives the weight less than each sieve size contained in 73 lb. of the stone. In order to make 100 lb. of combined aggregate we must add 27 lb. of sand all finer than $\frac{3}{16}$ in.; to get 26 per cent. passing No. 7 sieve, 24·5 lb. of this sand must be finer than No. 7 sieve since the stone has 1·5 lb. finer than No. 7; and the weights passing the smaller sieves must be 20·5, 14·5 lb., etc. Adding *D* and *E*, we get a grading that is sufficiently close to the type grading. By dividing the weights passing the smaller sieves in line *E* by 27 (that is, the 27 lb. of sand) and multiplying by 100 we get the grading of the sand alone as given in line *G*, which is what was required.

This is a rather fine sand containing only 9·4 per cent. passing the $\frac{3}{16}$-in. sieve and retained on the No. 7 sieve. The usual proportion of this top size is not required in the sand because part of it is already supplied by the stone.

This is an important example. Reference will be made to it later in discussing concretes such as 1 : 2 : 4, 1 : 2½ : 5, 1 : 3 : 6, etc., and in connection with the use of fine sands. In practice a crushed stone having the grading taken in this example would contain small proportions of fines down to dust. But these have been eliminated from the example in order to simplify it as much as possible.

CHAPTER X

TYPE GRADINGS FOR AGGREGATES OF 2-IN. AND 3-IN. MAXIMUM SIZES

Standard of Workability.—Aggregates of these sizes are mostly used in mass concrete and with methods of placing that are different from those used in reinforced concrete. Heavy tamping or vibration is commonly used to compact such concretes. In preparing type gradings for aggregates of 2-in. and 3-in. maximum sizes, the author took account of this difference in methods of placing and adopted a different standard of workability from that used for $\frac{3}{4}$-in. and $1\frac{1}{2}$-in. aggregates. Instead of allowing for easy placing by rodding or spading, he adopted a degree of workability which requires that at least light tamping must be used to compact the concrete.

When easier workability is required it can be obtained by using the grading represented by the curve next above the type curve for the mix, and by using the proportion of water corresponding to the upper curve. Thus, to get easier workability with a mix of 1 bag of cement to 5 cu. ft. of combined aggregate, use grading No. 6 and the proportion of water corresponding to grading No. 6. The resulting concrete will be more easily placed than that made with the type grading (No. 5). At the same time the increase in fines and in water is not sufficient to cause more than a comparatively small reduction in the very high strength and density obtainable by using the type grading and tamping the concrete. In the case just mentioned, and when using a certain cement, the reduction in strength at 7 days would be from 6000 lb. per square inch to 5300 lb. per square inch.

Type Gradings.—*Figs.* 19 and 20 show the type gradings for aggregates of 2-in. and 3-in. maximum sizes. They were prepared for crushed stone (2 in. or 3 in. to $\frac{3}{16}$ in.) and natural sand (from $\frac{3}{16}$ in. down), because the use of very coarse gravel or cobbles is rare, but they can be used for such coarse gravels if required.

Figs. 20 and 22 show the relationship between N (cement content) and proportion of water for these maximum sizes. These diagrams may be used in precisely the same ways as those already given for $\frac{3}{4}$-in. aggregates.

Lower Proportions of Sand with Larger Maximum Sizes.—Comparison of *Figs.* 13, 14, 16, 17, 19 and 21 shows that the proportion of sand required in a mix of any one proportion of cement to combined aggregate decreases as the maximum size of particle increases. This is true even when an allowance is made for the lesser workability of concretes made with the type gradings given for 2-in. and 3-in. maximum sizes. Taking proportions of 112 lb. of cement to 6 cu. ft. of aggregate, we find that the percentages of sand ($< \frac{3}{16}$ in.) are, respectively,

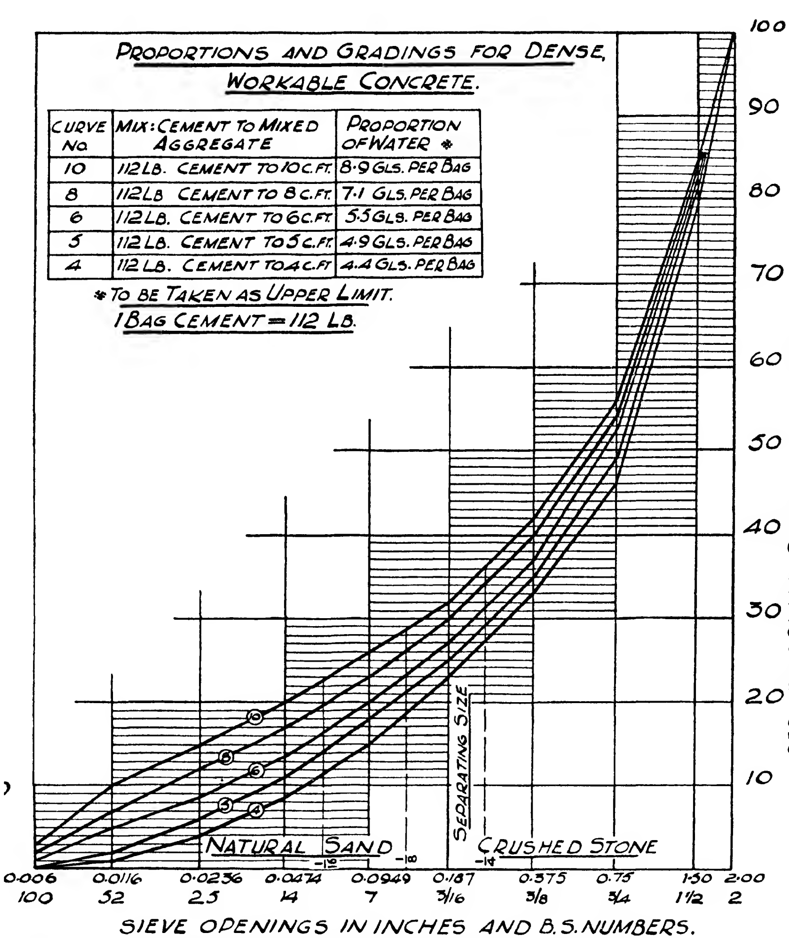


Fig. 19.—2-in. maximum size. Aggregates: Crushed stone (2 in. to

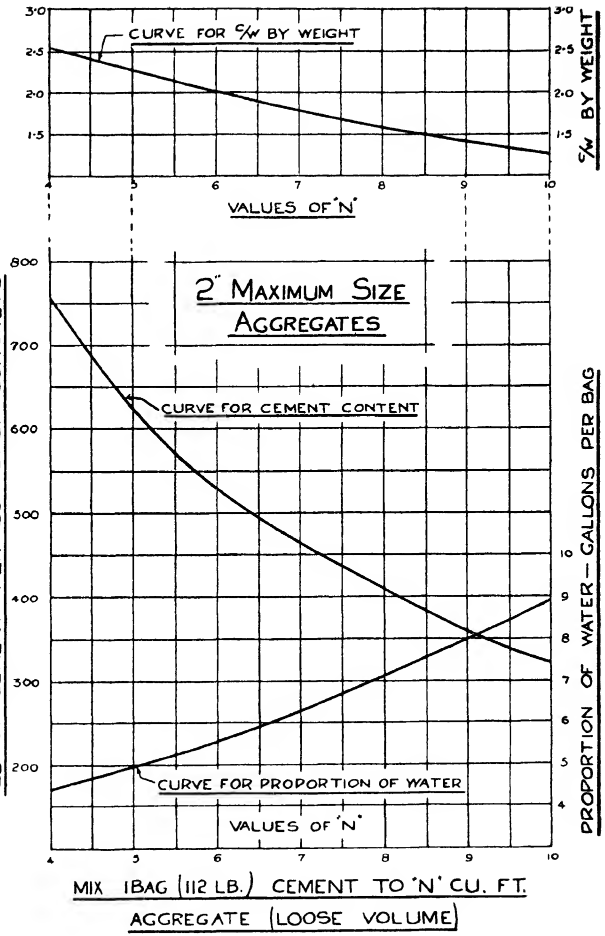


Fig. 20.

42 per cent. and 44 per cent. for ¾-in. gravel and crushed stone
33 per cent. and 35½ per cent. for 1½-in. ,, ,, ,, ,,
27 per cent. for 2-in. aggregate
24 per cent. for 3-in. ,,

Even when the workability with 2-in. and 3-in. aggregates is increased above that for the type grading by using the next higher grading curve (that is, No. 8 in this case), the percentage of sand for 2-in. aggregate is only 30 per cent. and for 3-in. aggregate only 27 per cent.

Lower Proportions of Water with Larger Maximum Sizes.—There is a corresponding reduction in the proportion of water required as the maximum size of the aggregate increases. For a mix of 112 lb. of cement to 6 cu. ft. of combined aggregate the following are the proportions corresponding to the various maximum sizes and kinds of aggregate.

Aggregate	Proportion of water (gallons per 112-lb. bag)
¾-in. gravel	7·5
¾-in. crushed stone	7·9
1½-in. gravel	6·9
1½-in. crushed stone	7·2
2-in. ,, ,, ...	5·5 (7·1 for 112 lb. to 8 cu. ft.)
3-in. ,, ,, ...	5·25 (6·5 ,, ,, ,,)

This means that while using the same proportions of cement to mixed aggregate and about the same workability, the strength of mass concrete can be increased by about 25 per cent. (from 3200 lb. to 4000 lb. per square inch) by changing from ¾-in. to 3-in. maximum size. If advantage is taken of placing the concrete made with the coarser aggregate by tamping or vibration, so that the type gradings for the coarser aggregate may be used, the strength can be increased by about 60 per cent.

Alternatively, for the same strength, the proportion of cement can be reduced by increasing the maximum size of the aggregate.

Increase in Weight per Cubic Foot.—By taking advantage of all the possibilities of size and methods of placing the weight per cubic foot of concrete may be increased from about 147 lb. per cubic foot to more than 155 lb. per cubic foot by increasing the maximum particle size from ¾ in. to 3 in. This is for the same proportion of cement to aggregate and for aggregates of the same specific gravity.

Possibilities of Reducing Shrinkage.—Shrinkage of concrete during hardening depends partly on its cement content and partly on the proportion of water to cement. The lower these are the less the shrinkage. What has been said previously indicates the possibilities of reducing shrinkage by judicious reductions of cement and water made possible by the use of aggregates of the largest possible maximum size.

Example 7.—The following observations (partly taken from practice) illustrate improvements in quality and savings in cement which may be obtained by using larger aggregate.

In a concrete road the 6-in. thick bottom course was a 1 : 2 : 4 mix. The

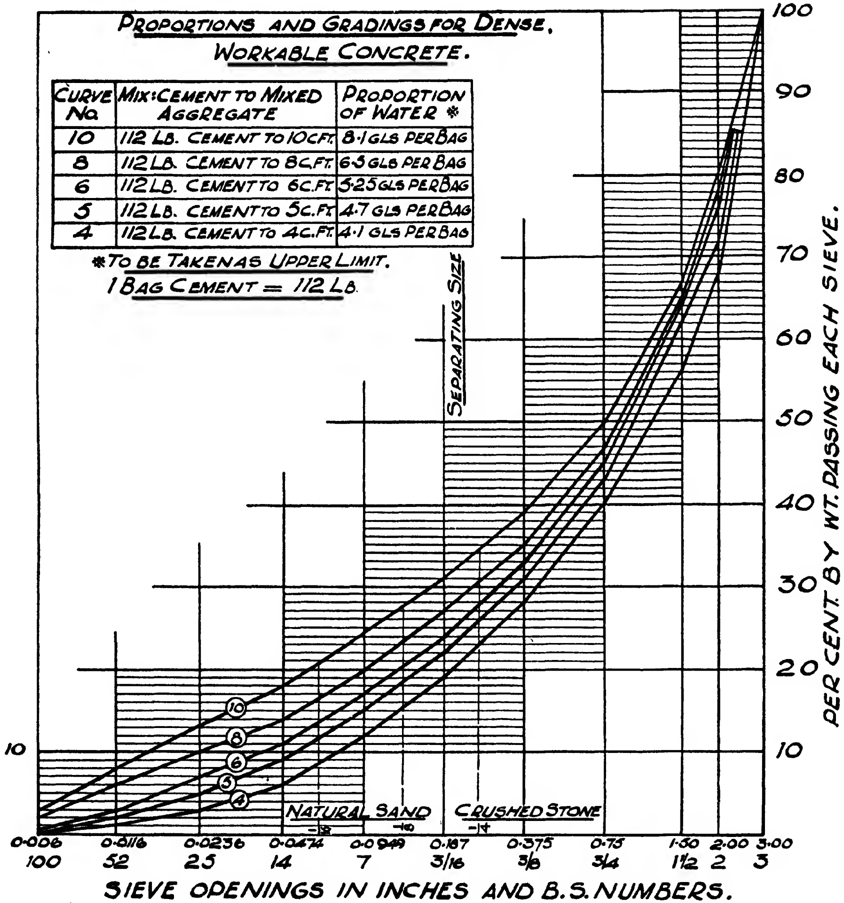


Fig. 21.—3-in. maximum size. Aggregates: Crushed stone (3 in. to $\frac{3}{16}$ in.) and sand ($\frac{1}{4}$ in. to 0).

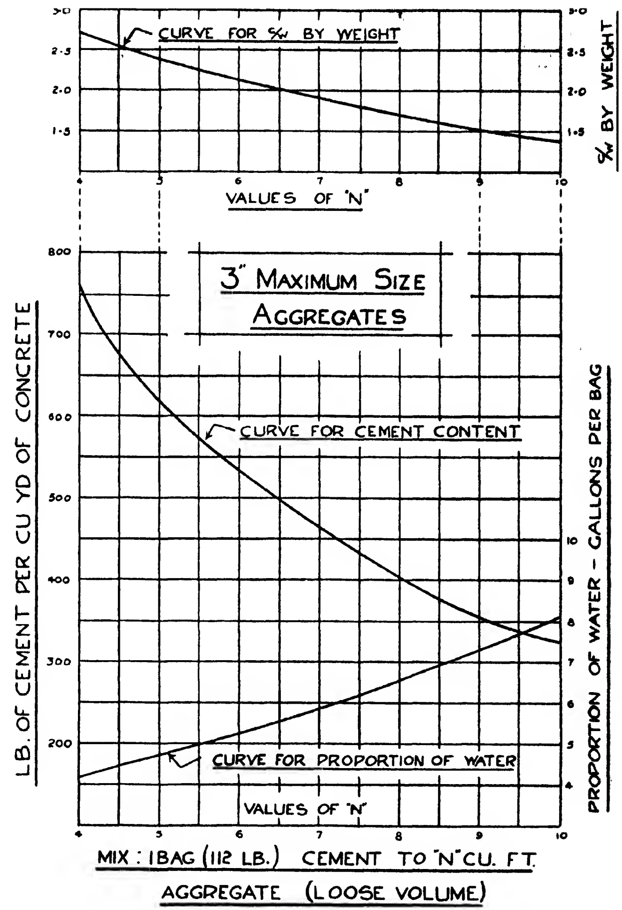


Fig. 22.

cement content worked out at 505 lb. per cubic yard, and the proportion of water used was 7·2 gallons per 112 lb. of cement. The coarse aggregate was $1\frac{1}{2}$ in. to $\frac{3}{8}$ in.

The 2-in. thick top course was in the proportions 1 : 2 : 3·44. The cement content of this was 610 lb. per cubic yard, and the proportion of water was 6 gallons per bag of cement. The coarse aggregate was nominally $\frac{3}{4}$ in. to $\frac{3}{16}$ in. and the same kind of crushed stone as that used in the bottom course.

The average cement content may be found thus:

18 sq. yd. 6 in. thick = 3 cu. yd. @ 505 lb. per cubic yard require	1515 lb. of cement
18 sq. yd. 2 in. thick = 1 cu. yd. @ 610 lb. per cubic yard require	610 lb. of cement
18 sq. yd. 8 in. thick = 4 cu. yd. contain	2125 lb. of cement

or 531 lb. of cement per cubic yard.

Fig. 20 for 2-in. aggregate shows that a concrete containing 531 lb. of cement per cubic yard is got from a mix of 1 bag of cement to 6 cu. ft. of 2-in. aggregate with $5\frac{1}{2}$ gallons of water per bag of cement.

Fig. 22 for 3-in. aggregate shows that a concrete with 531 lb. of cement per cubic yard is got from a mix of 1 bag of cement to 6 cu. ft. of 3-in. aggregate with $5\frac{1}{4}$ gallons of water per bag.

Therefore, if the road had been laid in one 8-in. course of concrete mixed in the proportion of 1 bag of cement to 6 cu. ft. of 2-in. or 3-in. aggregate properly graded, a stronger concrete than the wearing coat could have been made with the same cement content.

Assuming that the strength of the concrete in the top course was satisfactory, and, therefore, that the proportion of water used (6 gallons per bag) was not too high, we can see whether cement could have been saved.

From *Fig.* 22 we read that 6 gallons of water per bag of cement is the proportion of water for a mix of 1 bag of cement to 7·2 cu. ft. of 3-in. aggregate properly graded. The same diagram shows that this mix would yield concrete containing 450 lb. of cement per cubic yard. That is, a concrete equal in strength to that actually used in the top coat could have been made by using a mix of 1 bag of cement to 7·2 cu. ft. of 3-in. aggregate of the type grading, and at the same time 81 lb. of cement (531 lb.–450 lb.) would have been saved in each cubic yard of the road. In a mile of road 21 ft. wide and 8 in. thick this saving would amount to 99 tons of cement. At the same time the whole of the concrete would have been as strong as the top course actually laid and much stronger than the bottom course.

The sand actually used in the road was extremely fine. If a coarser sand had been used the proportion of water could have been slightly lower in the top coat; the proportion of cement required in the single coat would then have been a little higher; and the saving in cement would have been less. The example is favourable to the single coat. It shows, however, that it is worth while considering a single-coat road with 2-in. or 3-in. aggregate when a hard-wearing stone is available locally.

The same argument can be extended to other applications of mass concrete and to concrete products. In general, the largest size of aggregate that is otherwise allowable should be used. By doing so stronger and denser concrete can be made and subsequent shrinkage reduced.

CHAPTER XI

SEPARATE GRADINGS OF FINE AND COARSE AGGREGATES

It is easy to calculate the separate gradings of the fine and coarse aggregates in a combined aggregate of which the grading is known. To get the grading of the fine aggregate one divides each of the percentages passing the $\frac{3}{16}$-in. and smaller sieves by the percentage passing the $\frac{3}{16}$-in. sieve and multiplies each quotient by 100. To get the grading of the coarse aggregate one first subtracts the percentage passing the $\frac{3}{16}$-in. sieve from the percentages passing the sieves larger than $\frac{3}{16}$ in., and then divides each of the remainders by the largest remainder and multiplies each quotient by 100.

Thus, if we take curve No. 4 of *Fig.* 13, we find

Percentage passing $\frac{3}{8}$ in. less percentage passing $\frac{3}{16}$ in. $= 51 - 32 = 19$
Percentage passing $\frac{3}{4}$ in. less percentage passing $\frac{3}{16}$ in. $= 100 - 32 = 68$

$\frac{19}{68} \times 100 = 28$ per cent. (see point No. 4 on diagram for gravel in *Fig.* 24).

$\frac{68}{68} \times 100 = 100$ per cent.

The method of doing this has been fully illustrated towards the end of Example No. 5.

It is useful to have this done for the sand parts of the type gradings, so that one may be able to compare the grading of a sample of sand with the sand grading derived from a particular type curve. By such a comparison it can often be decided quickly whether a sand is suitable for use in a particular case. Similarly for coarse aggregates.

Sand Gradings for Use with $\frac{3}{4}$-in. and $1\frac{1}{2}$-in. Aggregates.

It is so easy to calculate a sand grading from a type curve that it is unnecessary to give diagrams of all the sand gradings. *Fig.* 23 is given to show the limits between which sand gradings should ordinarily lie in order that they may be likely to fit in with the type gradings as far as $\frac{3}{4}$-in. and $1\frac{1}{2}$-in. maximum sizes are concerned.

Limitations.—The boundaries of the central part of *Fig.* 23 are approximately the envelopes of the sand gradings calculated from curves Nos. 4, 5, 6, 8, and 10 on the four diagrams of gradings for $\frac{3}{4}$-in. and $1\frac{1}{2}$-in. gravel and crushed stone aggregates. That is, the gradings of all the sand parts of the recommended aggregates lie within the central part of *Fig.* 23. In general, the sand parts of the aggregates for the richer mixes lie in the lower part of this zone, and those for the leaner mixes in the upper part. For example, the grading of the sand part of type grading No. 4 for $\frac{3}{4}$-in. gravel is 0, 11, 31·2, 50, 72, 100, where these numbers are the percentages by weight passing the B.S. sieves 100, 52, 25, 14, 7, $\frac{3}{16}$ in. respectively. This is for a rich mix and it lies in the lower part of the

zone. The grading of the sand part of type grading No. 10 for ¾-in. crushed stone is 5·8, 28·2, 52·4, 63, 78·5, 100 : this is for a lean mix and it lies near the upper boundary.

On referring to the zone between a pair of adjacent curves of any of the

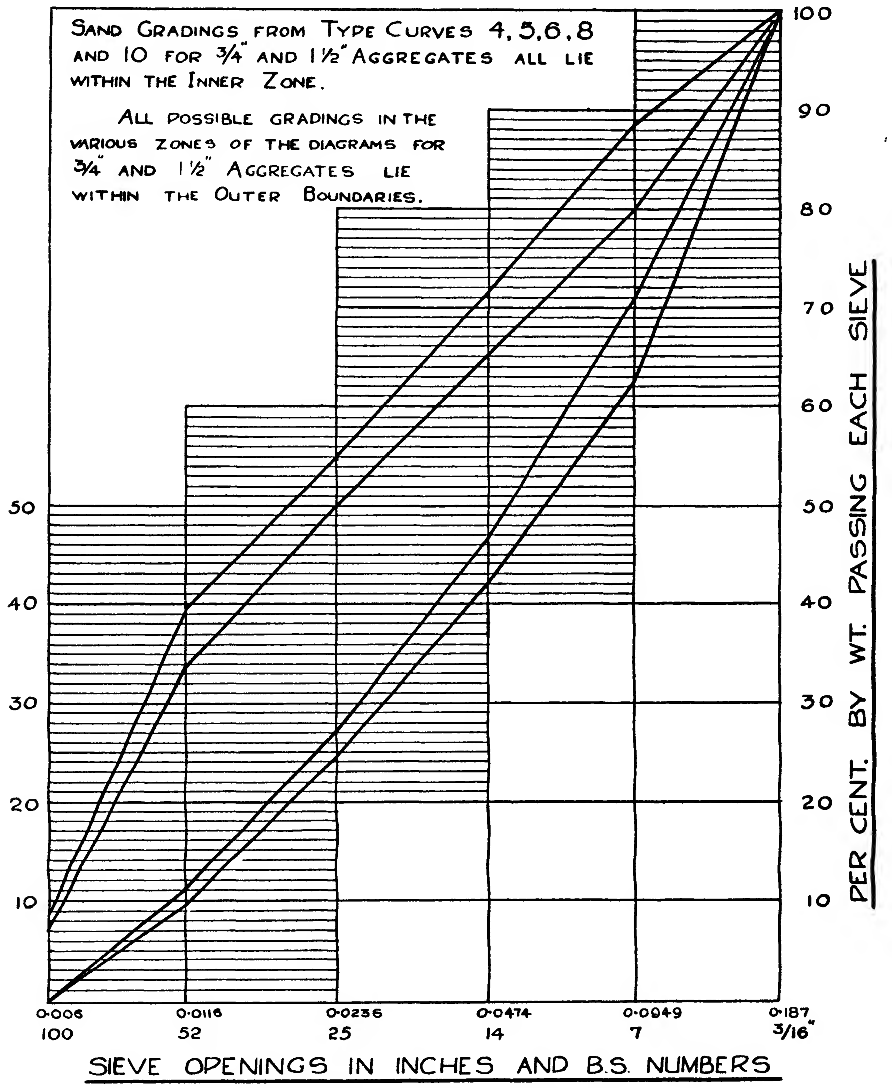


Fig. 23.—Gradings of Sands.

grading diagrams, say curves Nos. 5 and 6 of *Fig.* 15, it will be seen that various curves can be drawn within the zone representing different aggregate gradings. Consider a curve following curve No. 5 on the right-hand side of the separating size and following curve No. 6 on the left-hand side of the ordinate for sieve

No. 7. The percentages passing the sieves from 100 to $\frac{3}{16}$ in. are 0·5, 8, 18, 24·5, 32, and 37.

The grading of the sand in this aggregate is got by dividing each of these figures by 37 and multiplying by 100 and is 1·3, 21·6, 48·6, 66·2, 86·5, 100.

This is a fine sand, having a small proportion of particles passing the $\frac{3}{16}$-in. sieve and retained on sieve No. 7. It is finer than the sand part of curve No. 6 because the same numbers are divided by 37 instead of by 42, and therefore higher percentages are found to pass the various sieves.

Alternatively we may consider the curve that follows No. 6 on the right-hand side of the separating line and No. 5 on the left of the ordinate for sieve No. 7. We then get the percentages passing the sieves from No. 100 to $\frac{3}{16}$ in. as 0, 6, 14·5, 22, 28·5, 42.

On dividing by 42 and multiplying by 100, we get the series 0, 14·3, 34·5, 52·4, 67·8, 100, which is the grading of a coarse sand.

By taking intermediate curves different sand gradings can be found. Those just worked out are the finest and the coarsest that can be found in the zone.

By repeating this calculation for all the zones of *Figs.* 13, 14, 16, and 17 the gradings of all the finest and coarsest sands in the various zones can be found. By plotting all these extreme sand gradings and drawing curves to envelop them the outer boundaries of *Fig.* 23 were found.

All possible sand gradings that can be found in the zones of *Figs.* 13, 14, 16, and 17 for $\frac{3}{4}$-in. and $1\frac{1}{2}$-in. aggregates are included between the outer boundaries of *Fig.* 23.

Exceptions.—The preceding remark might be taken to mean that if the grading curve of a sand falls outside the boundaries of *Fig.* 23 that sand should not be used, because it is either too fine or too coarse. In general this is true, but there are particular cases where sands that are finer than any within the boundaries of *Fig.* 23 may be used successfully.

The limitations of *Fig.* 23 apply only in the case of cleanly separated aggregates, that is, aggregates so well screened that all the particles of sand are smaller than $\frac{3}{16}$ in., and all the particles of coarse aggregate are retained on a $\frac{3}{16}$-in. sieve. In practice coarse aggregates are often not so well screened, and frequently contain several per cent. of particles that pass a $\frac{3}{16}$-in. sieve and are retained on a No. 7 or even on the No. 14 sieve, with fractional percentages passing the smaller sieves. The grading of such an aggregate was illustrated in Example No. 6. This is almost bound to happen when crushed stone or gravel is screened while moist, as some of the smaller particles then adhere to bigger ones and remain in the coarser aggregate.

The following example illustrates a case in which a sand having a grading curve lying partly outside the boundaries of *Fig.* 23 may be used successfully, because fines carried by the coarse aggregate improve the grading of the " sand " part of the combined aggregate.

Example 8.—Suppose that a sand all smaller than $\frac{3}{16}$ in. is so fine that 89 per cent. by weight passes a No. 7 sieve ; that is, 11 per cent. of it passes a $\frac{3}{16}$-in. sieve and is retained on a No. 7 sieve. Suppose further that this is to be mixed with a crushed stone which contains 10 per cent. of particles passing the $\frac{3}{16}$-in. sieve and retained on No. 7, and that the proportion by weight of the sand and crushed stone are as 35 to 65.

35 lb. of the sand contains $0·11 \times 35 = 3·8$ lb. between $\frac{3}{16}$ in. and No. 7.
65 lb. of the stone contains $0·10 \times 65 = 6·5$ lb. of $\frac{3}{16}$-in. to No. 7.
100 lb. of the combined aggregate contains 10·3 lb. of $\frac{3}{16}$-in. to No. 7.
But only 41·5 lb. of the 100 lb. is less than $\frac{3}{16}$ in.; therefore, the part less than $\frac{3}{16}$ in. contains 24·8 per cent. between $\frac{3}{16}$ in. and No. 7. That is, the percentage passing No. 7 is 75·6 per cent., which is within the inner boundaries in *Fig.* 23.

EXAMPLE 9.—A further example will illustrate this more fully. The first line of the following table gives the grading of a fine sand *A*. Part of the grading curve of this sand, if drawn on *Fig.* 23, would lie above the extreme upper boundary. The second line gives the grading of a crushed stone *B* which has 14 per cent. by weight passing a $\frac{3}{16}$-in. sieve. Suppose that these are to be mixed in the proportion of 1 volume of sand to 2 volumes of stone, or 35 lb. of sand to 65 lb. of stone. *C* is the grading of the mixture which has 44·1 per cent. passing the $\frac{3}{16}$-in. sieve. *D* is the calculated grading of the part of *C* finer than $\frac{3}{16}$ in.

Sieves	100	52	25	14	7	$\frac{3}{16}$ in.	$\frac{3}{8}$ in.	$\frac{3}{4}$ in.
Grading of sand *A* (per cent.)	6	30	56	73	90	100	—	—
Grading of crushed stone *B* (per cent.)	0	0	0·5	1	3	14	50	100
35 lb. of *A* . . lb.	2·1	11	19·6	25·5	31·5	35	35	35 weight (lb.) passing each sieve
65 lb. of *B* . . lb.	0	0	0·3	0·6	2·0	9·1	32·5	65 weight (lb.) passing each sieve
Grading of mix *C* (per cent.)	2·1	11	19·9	26·1	33·5	44·1	67·5	100
Grading of part less than $\frac{3}{16}$ in. *D*	4·8	25	45·2	59·2	76	100	—	—

This last grading is well within the inner boundaries of *Fig.* 23. The particles finer than $\frac{3}{16}$ in. in the coarse aggregate combine with the sand to form an "effective sand" having a grading curve lying not far from the middle of the inner zone of *Fig.* 23. This explains why quite good concrete has often been made with sands that are too fine if judged by *Fig.* 23 or by many specifications that are in use.

It also shows that aggregates, which taken separately might be described as badly graded, may be combined to form a mixed aggregate having an excellent grading. Especially on small works in localities where aggregates are not developed there is often little choice of materials, and unpromising materials have to be used. The best possible use of such materials can be made by applying the principles so far described and illustrated, provided the concrete specification is not so rigid as to prevent alteration of the relative proportions of fine and coarse aggregates.

"Average Sand."—The sand grading represented by the sequence 4, 24, 40, 56, 75, 100 represents fairly closely the centre line between the outer boundaries of *Fig.* 23. An easier sequence to remember is 0, 20, 40, 60, 80, 100. Either is a useful sequence to have in one's mind as an "average sand grading" when examining results of sieve analyses of sands.

Sands for Use with 2-in. and 3-in. Aggregates.—The methods that have been illustrated for $\frac{3}{4}$-in. and $1\frac{1}{2}$-in. aggregates may be applied also to sands

for 2-in. and 3-in. aggregates. However, with these maximum sizes and the kind of workability usually required the proportion of sand ($< \frac{3}{16}$ in.) necessary is much smaller than for $\frac{3}{4}$-in. and $1\frac{1}{2}$-in. aggregates. Consequently the effects of differences in the grading of the sand alone are not so serious as for the smaller maximum sizes which require more sand. A diagram similar to *Fig.* 23 pre-

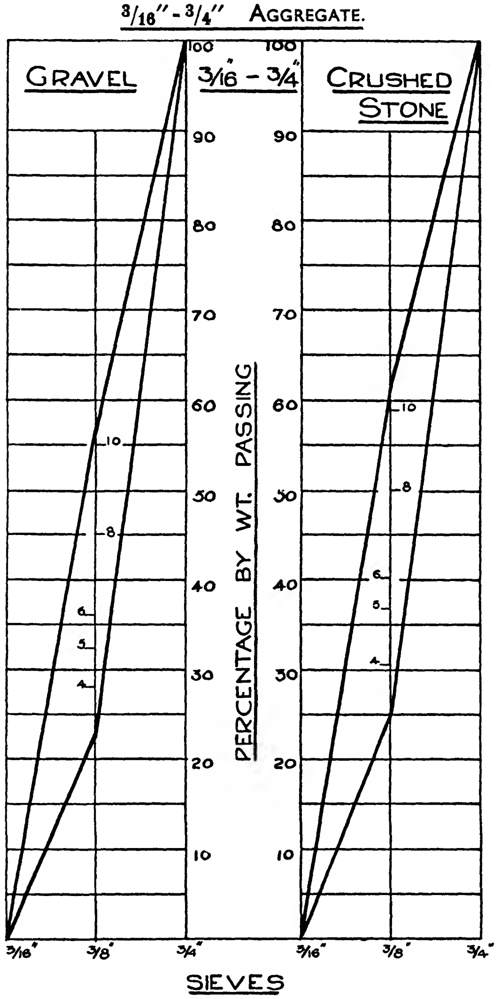


Fig. 24.

pared from the gradings of *Figs.* 19 and 21 has its boundaries wider apart than those of *Fig.* 23, showing that sands that are both coarser and finer than those allowable with $\frac{3}{4}$-in. and $1\frac{1}{2}$-in. maximum sizes may be safely used with 2-in. and 3-in. sizes. The limitations of the inner zone of *Fig.* 23 can be applied to sands intended for use with 2-in. and 3-in. aggregates, except for rich mixes in which coarser sands may be used, and in special cases.

Coarse Aggregates taken Separately.

¾-in. and 1½-in. Maximum Sizes.—*Figs.* 24 and 25 show the gradings of coarse aggregates above $\frac{3}{16}$ in. derived from the type gradings for ¾-in. and 1½-in. aggregates and the limits of the most extreme gradings possible in the

$^3/_{16}$"-$1^1/_2$" AGGREGATE.

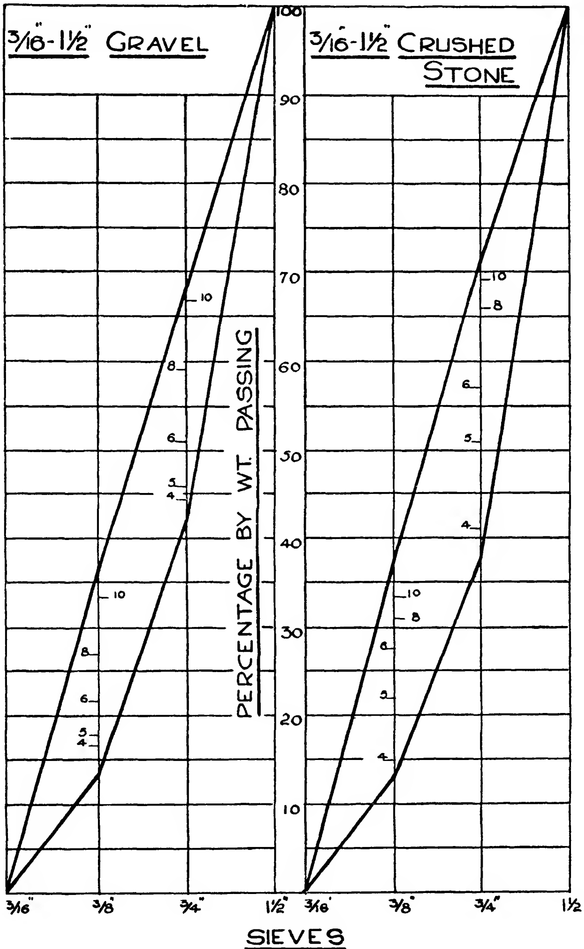


Fig. 25.

zones. These will be found useful in judging sieve analyses of separate coarse aggregates.

The numbers 4, 5, 6, 8, and 10 on the ⅜-in. ordinates in *Fig.* 24 indicate the points in which the grading curves calculated from the correspondingly numbered type curves of *Figs.* 13 and 14 cut those ordinates. The numbers on the ⅜-in. and ¾-in. ordinates in *Fig.* 25 are similarly related to the type curves of

Figs. 16 and 17. The bounding curves in each diagram indicate the most extreme gradings possible in any of the zones of the corresponding set of type curves.

The most notable point about *Fig.* 24 is the small proportion of $\frac{3}{8}$-in. to $\frac{3}{16}$-in. material required in aggregates of $\frac{3}{4}$-in. maximum size for rich and medium mixes, viz. 23 per cent. to 40 per cent. for mixes richer than 112 lb. of cement to

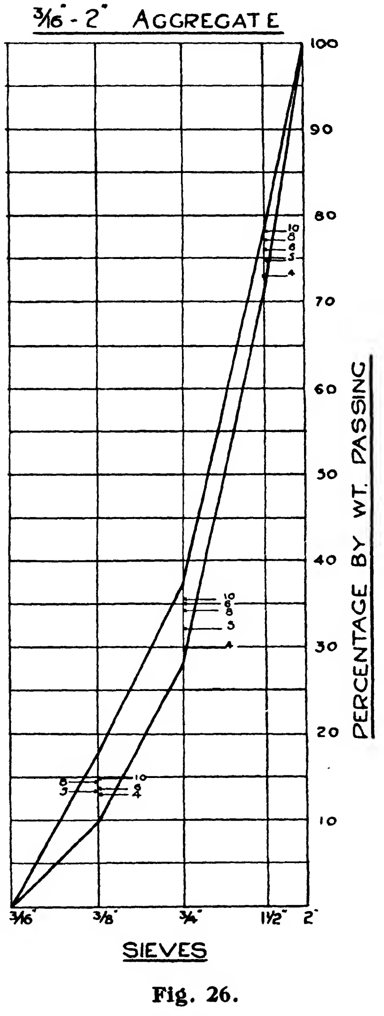


Fig. 26.

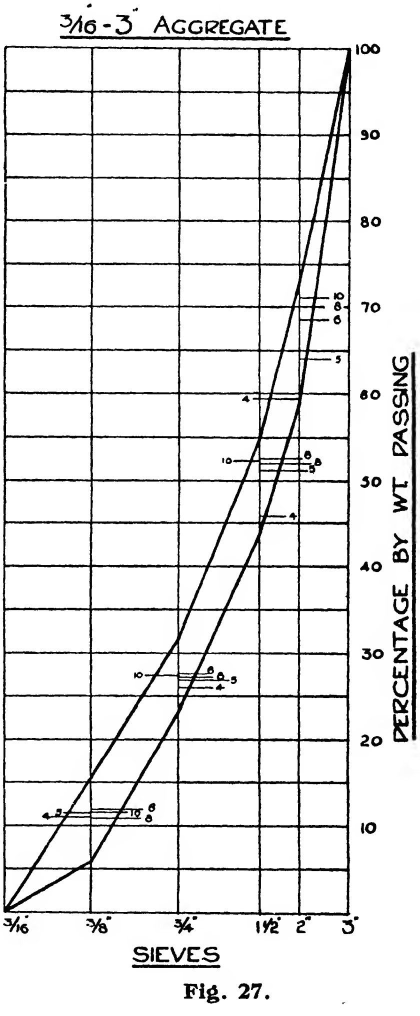


Fig. 27.

6 cu. ft. of combined aggregate. Even lower proportions can be used successfully. Much higher proportions are often used in practice with consequent loss of workability and density.

2-in. and 3-in. Maximum Sizes.—*Figs.* 26 and 27 show the gradings of coarse aggregates above $\frac{3}{16}$ in. derived from the type gradings for 2-in. and 3-in. aggregates.

CHAPTER XII

ONE VOLUME OF SAND TO TWO VOLUMES OF COARSE AGGREGATE

ONE volume of fine to two volumes of coarse is so commonly used with aggregates of $\frac{3}{4}$-in. to $1\frac{1}{2}$-in. maximum size that it is important to examine the grading curves of aggregates mixed in these proportions, and to compare them with the type gradings.

Dry sand generally weighs more per cubic foot than coarse aggregate containing no particles smaller than $\frac{3}{16}$ in. When the materials have about the same specific gravity, proportions by volume of 1 part of *dry* sand to two parts of coarse aggregate ($\frac{3}{4}$ in. or $1\frac{1}{2}$ in. maximum) correspond usually to proportions by weight of about 35, or slightly more, to 65 or slightly less; therefore, the grading curve of such a combined aggregate must cut the separating ordinate at or about the 35-per cent. point.

Effect of Specific Gravities of Aggregates.—The specific gravity of sand is nearly always close to 2·65. The specific gravity of coarse aggregates varies between about 2·6 and 2·9. When the specific gravity of the coarse aggregate is high the weights per cubic foot loose and dry of sand and coarse aggregate are nearly the same. Then the grading curve of a combined aggregate consisting of one volume of fine to two volumes of coarse aggregate cuts the separating line at a point between 33 per cent. and 35 per cent. In general, however, the point of intersection with the separating ordinate is close to 35 per cent.

Variations in Grading with Same Proportions.—This holds whether the sand is fine, medium, or coarse. If the sand is fine, it will have few particles between $\frac{3}{16}$ in. and No. 7-sieve size and this segment of the grading curve will be flat. If it is very coarse, it will have a high proportion of particles between $\frac{3}{16}$ in. and No. 7-sieve size and this segment of the grading curve will be steep. For a mixture of one volume of a fine sand with two volumes of a coarse aggregate nearly all larger than $\frac{3}{8}$ in. the grading curve would be flat on both sides of the separating line. A mixture of the same proportions of a coarse sand and a gravel or crushed stone having a high proportion of particles between $\frac{3}{16}$ in. and $\frac{3}{8}$ in. has a grading curve which intersects the separating ordinate steeply.

Therefore, even though the proportion of sand to coarse aggregate is fixed, the grading of the combined aggregate may vary between wide limits, being merely confined to passing through the 35-per cent. point on the separating line. Consequently the proportion of water and the workability and density of a concrete made with a fixed proportion of cement (that is, a fixed value of n) may vary considerably according as different sands and coarse aggregates are used, even though the relative proportions of cement, sand, and coarse aggregate remain constant.

Such Proportions not Generally Suitable with $\frac{3}{4}$-in. Aggregates.—

Numerous tests have shown that average concretes proportioned 1 : *n* : 2*n*, for *n* = 1½, 2, 2½, and 3, contain about the same proportions of cement per cubic yard as concretes made with the type gradings and proportions shown in the following table.

1 : *n* : 2*n*	Equivalent proportions of dry combined aggregate to cement
	Cu. ft. of aggregate to 112 lb. of cement
1 : 1½ : 3	4·9
1 : 2 : 4	6·25
1 : 2½ : 5	7·75
1 : 3 : 6	9·50

In *Figs.* 13 and 14 curves 5 to 10 cut the separating ordinate well above the 35-per cent. point. Therefore, with ¾-in. maximum size and $\frac{3}{16}$-in. separating size, the volume of sand must be more than half the volume of coarse aggregate except for the richest concretes. It follows that 1 : 2 : 4, 1 : 2½ : 5, and 1 : 3 : 6 concretes made with ¾-in. gravel and crushed stone cannot be workable unless the sand is fine—exceptionally fine for the leanest mixes. When the sand is fine enough the grading curve of the combined aggregate is flat to the left of the separating ordinate, and may rise above the type grading over the smaller sieve sizes. The concrete may then be workable, but the excess of fines reduces density, and the extra water required to wet them reduces the strength. We must conclude that 1 : *n* : 2*n* proportions by volume are not generally suitable for making dense and workable concrete with ¾-in. aggregates, especially ¾-in. crushed stone, except in rich mixes, such as 1 : 1¾ : 3½ and richer.

This applies only when the separating size is $\frac{3}{16}$ in. or larger and to cleanly separated aggregates. (Sometimes ⅛ in. is used as a separating size. The chief objection to this is the danger of getting far too high a proportion of particles between ⅛ in. and ¼ in. in the coarse aggregate, especially in crushed stone.) Frequently the coarse aggregate contains particles smaller than $\frac{3}{16}$ in. Then the percentage of the combined aggregate passing the $\frac{3}{16}$-in. sieve is greater than 35 per cent. by an amount depending on the proportion of fines contained in the coarse aggregate. As a result the grading curve of the combination may lie quite close to the appropriate type grading. This is well illustrated in Example 9, which is typical of many that the author has met in practice.

ALTERNATIVE.—When the local sands and ¾-in. coarse aggregate are unsuitable in the manner indicated above for 1 : *n* : 2*n* proportions, the proportion of sand to gravel or crushed stone should be altered so as to make the grading of the mixture approximate as closely as possible to the appropriate type grading. It may not be allowable to do this if 1 : *n* : 2*n* proportions are too rigidly specified. This is a strong argument in favour of a method of specifying that permits variations in the relative proportions of fine and coarse aggregates.

1 : *n* : 2*n* Proportions by Volume More Suitable with 1½-in. Aggregates.—In *Fig.* 16 the 35-per cent. point on the separating ordinate is nearly midway between curves Nos. 6 and 8; in *Fig.* 17 it is just under curve No. 6. Therefore, 1 : 1½ : 3 and 1 : 2 : 4 concretes are much more likely to be workable and dense with 1½-in. than with 3-in. aggregates, even when the sand tends to be coarse. With fine sands 1 : 2½ : 5 and 1 : 3 : 6 concretes are workable.

In general, 1 : *n* : 2*n* proportions are more satisfactory with 1½-in. than with ¾-in. aggregates.

Equivalent Proportions Preferable.—Better concretes of more consistent quality can be made by using the proportions of cement to mixed aggregates equivalent to the 1 : *n* : 2*n* proportions, and by proportioning the best available materials so that the combined aggregate is graded approximately to the proper type, than by adhering to 1 : *n* : 2*n* proportions.* Sometimes 1 : *n* : 2*n* proportions are so rigidly specified that they must be used. One should then choose aggregates that combine in the specified proportions to produce a grading approximating as closely as possible to the type grading for the equivalent proportion of cement to combined aggregate (see Example 5).

* *Equivalent proportions* are those which produce approximately the same cement content in the finished concrete. Thus, 1 : 2 : 4 proportions and 112 lb. of cement to 6¼ cu. ft. of combined aggregate are equivalent because each will make concrete containing about 505 lb. of cement per cubic yard. Proportions equivalent to 1 : 1½ : 3, 1 : 2 : 4, etc., are given in *Figs.* 13, 14, 16 and 17.

CHAPTER XIII

DECIDING PROPORTIONS

THE previous chapters and worked examples dealing with proportions are mainly concerned with cases in which the proportion of cement to combined aggregates or of cement to fine aggregate and to coarse aggregate is already fixed. In one example (No. 3, p. 51) it was assumed that the value of $\frac{c}{w}$ had been determined already, and it was shown how to determine the proportions of cement and aggregates. More guidance is necessary for the engineer who has to decide all the proportions.

He may be guided by consideration of one or more of the following qualities of the concrete, depending on which are the more important for the work in hand.

(1) Strength—which must be sufficient to carry the applied loads safely;
(2) Density—especially important where weight or water-tightness is necessary or where exposure is severe; and
(3) Workability—which must be sufficient to give good compaction and surface finish with the method of placing contemplated.

Designing for Strength.—Strength is the criterion most commonly used. *Table* 5 is a general guide to the proportions of cement to combined aggregate to be used for various purposes. It is based partly on " The Recommendations for a Code of Practice for Reinforced Concrete " as recommended by the Reinforced Concrete Structures Committee of the Building Research Board and partly on the proportions which are ordinarily used in practice. It gives sufficient guidance for most applications. Those who are accustomed to using $1 : n : 2n$ proportions will find their equivalents in *Table* 5 and on the grading diagrams.

The limits of proportions of water given in most cases in *Table* 5 cover the range from tamped concrete to easily workable concrete, and allow also for differences in absorption by aggregates. In two cases (" About 5·5 " and " About 6 ") they are for tamped or vibrated concrete only.

In special cases in which it is known that certain aggregates and a certain brand of cement will be used tests should be made of concretes made with these materials and three different proportions of water covering the range likely to be used. The proportion of water to cement and the proportions of the dry materials can then be determined as described already (Example 3, p. 51).

Designing for Density.—It often happens that density is more important than strength either because dead weight is necessary or because impermeability is important. The latter happens not only in water-retaining structures but also in reinforced structures in severe exposures where they are subject to repeated freezing and thawing or to attack by water, especially salt water or peaty water.

TABLE 5.

Purpose of Concrete	Number of cubic feet (N) of combined aggregate to be used with one (112 lb.) bag of cement	Proportion of water * (gallons per bag)	Reference number of corresponding mix in the "Recommendations for a Code of Practice"	Minimum requirements of the "Recommendations for a Code of Practice" for the 28-day strengths of 6-in. cubes (lb. per square inch)	
				Ordinary Grade	High Grade
Very heavily stressed members of structures	3·3	4·5 to 5·0	I	4388	5625
Heavily stressed members . . .	4·0	4·9 to 5·4	II	4163	5400
Important members of structures. Floors and walls of reservoirs and water towers, wearing coat of two-course concrete road, etc.	4·9	5·1 to 6·4	III	3825	4950
Concrete subjected to lower stresses. Roofs of reservoirs, footings, bottom course of concrete road, and ordinary concrete stressed to 600 lb. to 700 lb. per square inch	6¼	5·9 to 8·1	IV	3375	4275
Reinforced concrete piles . . .	4·9 to 6¼	5·1 to 8·1	—	—	—
Single course concrete road with aggregate of 1½-in. to 3-in. maximum size	5·9 to 6·3	About 5·5	—	—	—
Mass concrete foundations . . .	7·5 to 10	8 to 13	—	—	—
Concrete blocks	6¼ to 7½	About 6	—	—	—
Beds and haunching for sewer pipes	9 to 10	8 to 10	—	—	—

* Depends on whether concrete is to be tamped, vibrated or rodded, and on the absorption of water by aggregates. Lower limit for tamped or vibrated concrete. Upper limit for easily workable concrete.

The reinforcement must be protected against corrosion, otherwise the concrete covering the reinforcement will spall off when the steel rusts.

Where weight is the only consideration lean mixes and aggregates of the largest possible maximum size may be used. Where impermeability is also of some importance the proportions should be 1 bag of cement to 6¼ cu. ft. of combined aggregate (= 500 lb. to 520 lb. of cement per cubic yard of concrete). Leaner mixes are not advisable unless there is exceptionally close control of the work. Where impermeability is vital, and especially in reinforced work subjected to severe exposure, the proportions should be 1 bag of cement to 5·3 cu. ft. of combined aggregate, or richer (more than 580 lb. cement per cubic yard of concrete).

In all cases where density is important the proportion of water should be kept as low as possible.

Designing for Workability.—The degree of workability required depends mainly on the method of placing. Workability is controlled, for any proportion of cement to aggregate, by the grading of the aggregate and by the proportion of water. In general, it is advisable to use a grading represented by a curve coinciding with, or lying slightly above, the type curve for the proportion of cement. This has been discussed fully in Chapter VIII. Normally the proportion of water should be between the limits given in *Table* 5, tending towards the lower

limit for tamped or vibrated concrete and towards the upper for concrete that is to be placed by other methods.

Arbitrary Proportions.—Many designers are accustomed to arbitrary $1 : n : 2n$ proportions and think of the quality of concrete in terms of n. *Table* 5 will enable them (and those who use the " Recommendations for a Code of Practice ") to decide the equivalent proportions of cement to combined aggregate.

Cement Content.—Those who are accustomed to thinking of quality in terms of the cement content of the finished concrete can read from *Figs.* 15, 18, 20, or 22 the corresponding proportion of cement to combined aggregate necessary to give the cement content that they require.

Final Proportions.—Whatever his method of approach, by using the data and guidance already given, the engineer can arrive at the proportion of cement to combined aggregate, the proportion of water, and the grading of the aggregate. The next step is separation of the combined aggregate into its constituent proportions of fine and coarse. All the processes involved have been illustrated in previous chapters, and by following the procedure outlined the engineer can finally state in detail all the proportions of the materials, the grading of the combined aggregate, and, if necessary, the separate gradings of the fine and coarse aggregates.

CHAPTER XIV

SPECIFICATION

THE methods already outlined can be used with most ordinary specifications for concrete. But their use is facilitated either by modifying the usual clauses governing proportions, grading, and control on the site, or by using clauses similar to those suggested below. Of course, all the usual clauses relating to freedom from impurities, shape of particles, etc., should be included.

Grading of Fine Aggregate.—The following wording is suggested:

> "All fine aggregate shall pass through a $\frac{3}{16}$-in. B.S. sieve, and shall be graded from the largest to the smallest size to the satisfaction of the Engineer." . . . . (1)

This is sufficient, when taken in conjunction with the other clauses given later. The engineer may, however, specify limiting gradings for the sand, such as the inner limits of *Fig.* 23. But it is not wise to do this unless it is known that sands falling within these limits are economically available. There are districts in which sands having gradings within these limits cannot be found, all the sands being finer than the upper limit of the inner zone of *Fig.* 23. Yet it is possible to make good concrete with these sands (see Example 9). In certain cases, especially if the maximum size of the coarse aggregate is to be 2 in. or 3 in., it may be advisable to allow a larger separating size than $\frac{3}{16}$ in., depending on local conditions; for such cases the engineer may modify any of the suggested clauses to suit his own conditions.

Grading of Coarse Aggregate.—The following is suggested as a clause to control the grading of the coarse aggregate:

> "The coarse aggregate shall be retained on a $\frac{3}{16}$-in. B.S. sieve, and shall be graded to the satisfaction of the Engineer from this size to a maximum of either $\frac{3}{4}$ in. or $1\frac{1}{2}$ in. as specified for the different classes of concrete which follow. If specially suitable gravels are available, the Engineer may allow at his discretion the use of a gravel from which particles greater than the maximum specified size have been removed by screening, but from which the particles less than $\frac{3}{16}$ in. have not been removed. (When the coarse aggregate is crushed stone, and under special circumstances, the Engineer may allow a small proportion of the coarse aggregate to be smaller than $\frac{3}{16}$ in.)" . . . . (2)

This clause is worded on the assumption that there are to be different classes of concrete used in the works, and that the maximum particle size may be either $\frac{3}{4}$ in. or $1\frac{1}{2}$ in. No special limits for grading are fixed. The decision whether the grading is satisfactory or not is left to the engineer, and the contractor is not worried by details of grading. However, in the case of large works, where crushers

and screens are to be installed, it would be advisable to specify the grading of the coarse aggregate in detail and to state close limits.

Grading of Combined Aggregates.—The following clause is necessary not only to enable the engineer to obtain the type of grading required, but to some extent to protect the contractor against the fads of a crank.

> " The grading of the fine and coarse aggregates shall be such that, when they are mixed in the proportions decided for each class of concrete, the grading of the combined aggregate shall be suitable for making a dense concrete of appropriate workability with the proportions of cement and water with which the aggregate is to be used. The proportions of fine aggregate to coarse to be used in each class of concrete shall be decided by the Engineer." . . . . (3)

Here again the engineer may specify close grading limits instead of saying " suitable for making a dense concrete " etc., provided he knows it will be possible to get suitably graded fine and coarse aggregates at reasonable rates. But for ordinary purposes, and especially for small contracts, the foregoing clauses are adequate for controlling grading.

Samples of Aggregates.—A clause should be included requiring the contractor to supply samples of proposed aggregates for testing. Samples of sand should be not less than 50 lb., and samples of coarse aggregate not less than 100 lb. This should be stated in the specification, otherwise annoyance and delay may be caused by the receipt of ridiculously small samples. The amounts mentioned are necessary to provide representative samples in the case of coarse aggregates and to provide for making trial mixes to check the qualities of different concretes when tentative proportions have been calculated. Smaller preliminary samples may be accepted when a selection of one or more is to be made from a number of sands. But it is better to specify the amounts already stated.

Proportion of Cement.—To illustrate the clauses governing this it will be assumed that two classes of concrete are to be used, that these are to be equivalent respectively to $1 : 1\frac{1}{2} : 3$ and $1 : 2 : 4$ nominal proportions, and that there are to be two maximum sizes of aggregate, namely $\frac{3}{4}$ in. and $1\frac{1}{2}$ in., in each class. The following are the suggested clauses:

> " Classes of Concrete.—Two classes of concrete to be used in various parts of the works shall be designated respectively Class A and Class B." (4)
>
> " Gauging of Class A Concrete.—Class A concrete shall be so gauged as to contain not less than 630 lb. of cement in a cubic yard of finished concrete. A tolerance of $\pm$ 4 per cent. shall be allowable in the cement content of batches or of a day's output, but the amount specified must be maintained as an average. (Note: This will be produced approximately by proportions of one 112-lb. bag of cement to $4\frac{7}{8}$ cu. ft. of dry mixed aggregate. It is equivalent to the average concrete produced by $1 : 1\frac{1}{2} : 3$ proportions by loose volume.)
>
> " In this concrete the maximum size of the aggregate particles shall be $\frac{3}{4}$ in. or $1\frac{1}{2}$ in. as specified for particular parts of the works, and the concrete shall be designated accordingly as A $\frac{3}{4}$ in. or A $1\frac{1}{2}$ in." . . (5)
>
> " Gauging of Class B Concrete.—Class B concrete shall be so gauged as to contain not less than 505 lb. of cement in a cubic yard of finished concrete. A tolerance of $\pm$ 4 per cent. shall be allowed in the cement content of batches or of a day's output; but the amount specified above must be

maintained as an average. (Note: This will be produced approximately by proportions of one 112-lb. bag of cement to $6\frac{1}{4}$ cu. ft. of dry mixed aggregate. It is approximately equivalent to the concrete produced by 1 : 2 : 4 proportions by loose volume.)

" In this concrete the maximum size of the aggregate shall be either $\frac{3}{4}$ in. or $1\frac{1}{2}$ in. as specified for particular parts of the works, and the concrete shall be designated accordingly as B $\frac{3}{4}$ in. or B $1\frac{1}{2}$ in." . . (6)

Similar wording may be used to specify other classes of concrete by suitably altering the numbers. The second sentence of the explanatory note may be omitted. Its inclusion is recommended, because most contractors are familiar with $1 : n : 2n$ proportions, and this note helps them in pricing the bill of quantities.

Proportion of Water to Cement.—It is necessary to include a clause governing the proportions of water to cement and measuring water on the following lines:

" The proportion of water to cement in the various concretes shall not exceed those stated below.

" For Class A concrete, $6\frac{1}{8}$ gallons of water per 112-lb. bag of cement.

" For Class B $\frac{3}{4}$-in. concrete, 8 gallons of water per 112-lb. bag of cement.

" For Class B $1\frac{1}{2}$ in. concrete, $7\frac{1}{8}$ gallons of water per 112-lb. bag of cement.

" In general the proportion of water to cement shall be kept as low as possible." . . . . (7)

The actual quantities of water mentioned here should be altered to suit particular conditions.

Measuring Water.—" In measuring water for each batch of concrete allowance shall be made for water carried by the aggregates. The total water in the batch shall be deemed to consist of the water carried by the aggregates plus the water added in the mixer. This total water shall not exceed the amount stated for each class of concrete." . . . . . . (8)

Fixing Proportions.—It is necessary to have a clause giving the engineer the final decision on the proportions, and protecting the contractor as far as the cement content of the finished concrete is concerned. The following clause is suggested:

" For each of the above concretes the actual proportions of cement to sand and to coarse aggregate and of water to cement shall be determined by the Engineer as a result of tests carried out by him or his representative on samples of the actual aggregates to be used in the works. These proportions shall be such as to produce concrete containing the specified weight of cement per cubic yard of concrete for each class of concrete." . (9)

This clause is especially necessary, and should be inserted even if some of the others are omitted. It makes possible the use of the methods already described, even when arbitrary proportions are specified, especially if the clauses stating the proportions are followed by one stating that the engineer shall have the right to vary the relative proportions of sand and stone should the circumstances require it.

Strength and Density.—If strengths are to be specified the specification of the " Recommendations for a Code of Practice " for making, curing, and dis-

patching cubes may be used. For works control purposes it is important to specify that the weight per cubic foot of the fresh concrete shall exceed a certain amount. The weight to be specified depends on the maximum particle size and on the specific gravities of the aggregates. The weights given in the following clause are based on the specific gravities of both fine and coarse aggregates being about 2·65.

"Tests for Unit Weight of Concrete.—Tests to determine the weight per cubic foot of the freshly mixed concrete shall be carried out on the works daily or oftener as required.

"For these tests the Contractor shall supply a cylindrical measuring bucket of ½ cu. ft. capacity and weighing apparatus capable of weighing up to 100 lb.

"The bucket shall be made of stout welded sheet metal, reinforced on the outside with circumferential bands at the top and bottom and four vertical strips. The bottom of the bucket shall be flat. The internal diameter shall be 10½ in. and the internal depth 10 in. The rim of the bucket shall be in a plane truly perpendicular to the sides of the bucket.

"In carrying out the test the ½-cu. ft. bucket shall be filled with freshly mixed concrete taken from an ordinary batch. The method of filling the bucket shall be as nearly as possible the same as that adopted for filling the shuttering, the same kind of rodding, spading, tamping, or vibration being adopted as far as possible.

"The top of the concrete in the bucket shall be struck off and smoothed flush with the rim of the bucket. The bucket full of concrete shall then be weighed. By subtracting the known weight of the bucket from the total weight, the weight of the ½ cu. ft. of fresh concrete in the bucket shall be determined. Twice this weight shall be taken as the weight per cubic foot of the fresh concrete.

"The weight per cubic foot of the different classes of concrete shall comply with the requirements of the following schedule:

Class	Weight per cubic foot
A ¾ in.	Not less than 146 lb.
A 1½ in.	,, ,, 147 lb.
B ¾ in.	,, ,, 146 lb.
B 1½ in.	,, ,, 147 lb."

. . . . (10)

The actual weights to be inserted in this schedule depend, as stated already, on the maximum particle size and on the specific gravities of the aggregates, and also on the proportion of cement. The weight used for lean mixes should be lower than that for medium mixes; for example, if a concrete containing 350 lb. of cement per cubic yard were included in the above schedule the weight per cubic foot to be specified for it would be "not less than 145 lb."

Surface Finish.—To ensure control of workability it is advisable to include the following clause:

"All finished surfaces of concrete shall be smooth and free from visible holes." . . . . (11)

So long as the concrete is workable enough to satisfy the requirements of this clause and dense enough to satisfy the requirements of Clause 10, its quality must be good for concrete of its cement content.

CHAPTER XV

WORKS CONTROL

WHEN actual construction work is about to be started samples of the proposed aggregates should be obtained and tested. Particular attention should be paid to samples of sand, which, as well as being sieved, should be tested for organic matter and silt content by the methods specified in the " Recommendations for a Code of Practice."

When samples of two or more sands are supplied it is generally easy to decide between them. Sometimes, however, it may be difficult to decide which of two samples of sand is the better. The following example illustrates such a case.

Example 10.

The specified proportions of sand and combined aggregate were 112 lb. of cement to $5\frac{2}{3}$ cu. ft. of combined aggregate. Three samples of aggregate *A*, *B*, and *C* were submitted for test. *A* was a fine sand having the grading given in line 4 of *Table* 6. *B* was a coarse sand having the grading

TABLE 6.

No.	Sieves	100	52	25	14	7	$\frac{3}{16}$ in.	$\frac{3}{8}$ in.	$\frac{3}{4}$ in.
	1 bag to $5\frac{2}{3}$ cu. ft.								
1	Type	0·5	7·5	17·0	23·5	*31*	*40*	61	100
2	Sand part	0·1	19	42·5	60	77·5	100	—	—
3	Gravel part	—	—	—	—	—	0	35	100
4	Sand *A*	3	25	50	70	88	100	—	—
5	Sand *B*	0·5	15	34	55	74	100	—	—
6	Gravel *C*	—	—	—	—	—	0	32	100
	Trial No. 1.								
7	40 lb. of *A*	1·2	10	20	28	35·2	40	40	40
8	60 lb. of *C*	—	—	—	—	—	0	19	60
9	40 lb. of *A* + 60 lb. of *C*	1·2	10	20	28	35·2	40	59	100
10	Difference from Type	+ 0·7	+ 2·5	+ 3	+ 4·5	+ 4·2	—	− 2	—
	Trial No. 2.								
11	35 lb. of *A*	1·1	8·7	17·5	24·5	30·8	35	35	35
12	65 lb. of *C*	—	—	—	—	—	0	20·8	65
13	35 lb. of *A* + 65 lb. of *C*	1·1	8·7	17·5	24·5	30·8	35	55·8	100
14	Difference from Type	+ 0·6	+ 1·2	+ 0·5	+ 1	− 0·2	− 5	− 5·2	—
	Trial No. 3.								
15	43 lb. of *B*	0·2	6·5	14·6	23·6	31·8	43	43	43
16	57 lb. of *C*	—	—	—	—	—	0	18·2	57
17	43 lb. of *B* + 57 lb. of *C*	0·2	6·5	14·6	23·6	31·8	43	61·2	100
18	Difference from Type	− 0·3	− 1	− 2·4	+ 0·1	+ 0·8	+ 3	+ 0·2	—

given in line 5 of *Table* 6. *C* was a screened gravel having the grading given in line 6 of *Table* 6. A report was required about the suitability of the aggregates, which sand was preferable, and, if the aggregates were suitable, the proportions in which they should be used.

The type grading for $\frac{3}{4}$-in. gravel and sand for a mix of 112 lb. of cement to $5\frac{5}{8}$ cu. ft. of aggregate is given in line 1 of *Table* 6. The next two lines give the gradings of the separate aggregates calculated from the type grading.

Comparison of lines 3 and 6 shows that the grading of the sample of gravel is excellent, being almost identical with that calculated from the type grading.

Not so with the sands: *A* is finer and *B* coarser than the grading calculated from the type.

Yet neither is to be judged by this alone. It is necessary to try the effects of mixing different proportions of each sand with the gravel to determine whether it is possible to get a mixed aggregate having a grading close to the type grading.

Sand *A*.—The first trial is of 40 lb. of sand *A* with 60 lb. of *C*. This is done in lines 7, 8, and 9. The figures in line 7 are got by multiplying those in line 4 by $\frac{40}{100}$, and those in line 8 by multiplying those in line 6 by $\frac{60}{100}$. The figures in line 9 are the sums of those in lines 7 and 8, and give the grading of the combined aggregate. Line 10 shows that this has too much passing sieves Nos. 7, 14, 25, and 52. The differences in the percentages passing the $\frac{3}{8}$-in. and No. 100 sieves are negligible. This would make an easily workable concrete, but the excess of fines would require extra water and reduce both the strength and the density.

A better grading may be got by mixing 35 lb. of *A* with 65 lb. of *C*. The result of this trial is given in line 13, and the differences from the type grading in line 14. The only serious difference is $-$ 5 per cent. in the amount passing the $\frac{3}{16}$-in. sieve. The difference of $-$ 5·2 per cent. in the amount passing the $\frac{3}{8}$-in. sieve is not serious; it is beneficial to some extent because it helps to keep the proportion of $\frac{3}{8}$-in. to $\frac{3}{16}$-in. particles nearly correct. The excess of coarse particles, however, is set off by the smaller proportions of $\frac{3}{16}$-in. to No. 7 particles (4·2 per cent. instead of 9 per cent.) and the small excess passing each of the sieves No. 7 to No. 100. Concrete made with this aggregate should be of about the same quality as that made with the type gradings. It should be both workable and dense and should require about the same proportion of water as concrete made with the type grading. Therefore, sand *A* could be used; but the proportions should be 35 lb. of *A* to 65 lb. of *C* instead of 40 lb. to 60 lb.

Sand *B*.—Sand *B* is coarse; it is lacking in the smallest sizes. Therefore if this were mixed with *C* in the proportions 40 to 60 by weight the mixed aggregate would have insufficient fines. Instead we try to make the percentage passing the No. 14 sieve nearly the same as that in the type grading. A simple calculation shows that this requires about 43 lb. of sand mixed with 57 lb. of gravel. The grading of the mixed aggregate resulting from this combination is given in line 17. The differences from the type are given in line 18. There is more sand, but less of the smallest sizes, than in the type grading. One would expect this to be slightly less workable than concrete made with the type grading, and the general difference in quality to be slight. Therefore, sand *B* could be used in the proportions of 43 lb. of *B* to 57 lb. of gravel *C*.

So far the principal lesson of this example is that a sand should not be judged

solely on its own grading, and that grading of the sand must be considered in relation to that of the coarse aggregate with which it is to be used.

Trial Mixes.—Trial mixes made with 35 lb. of *A* and 65 lb. of *C* and with 43 lb. of *B* and 57 lb. of *C* showed very little difference in quality. The proportion of water for the first was $6\frac{1}{2}$ gallons per bag and for the second 6·44 gallons per bag. The cement contents of the fresh concretes were 558 lb. per cubic yard and 563 lb. per cubic yard respectively; this difference, being well within the limits of experimental error, is negligible. No measurable difference of slump or flow was found. Each concrete weighed 150 lb. per cubic foot. The only noticeable difference was that it was easier to get a good finish on the top surface of cubes with the first concrete than with the second. Because good surface finish was important in the work for which this concrete was intended, it was decided to recommend the use of sand *A*.

Proportions.—Sand *A* weighed 105 lb. per cubic foot loose when dry. Gravel *C* weighed 97·5 lb. per cubic foot loose when dry. The mixed aggregate containing 35 lb. of $A + 65$ lb. of *C* weighed 114 lb. per cubic foot loose when dry.

The specified proportions were:

112 lb. of cement to $5\frac{2}{3}$ cu. ft. of dry combined aggregate, that is,

112 lb. of cement to $114 \times 5\frac{2}{3} = 646$ lb. of mixed aggregate.

646 lb. of mixed aggregate contain $646 \times \frac{35}{100} = 226$ lb. of sand *A* and $646 \times \frac{65}{100} = 420$ lb. of gravel *C*.

The proportions by weight are:

112 lb. of cement : 226 lb. of sand *A* : 420 lb. of gravel *C*.

Since the sand weighs 105 lb. per cubic foot and the gravel 97·5 lb. per cubic foot, these become

112 lb. of cement : 2·15 cu. ft. of *dry* sand *A* : 4·31 cu. ft. of gravel *C*

or

112 lb. of cement : $2\frac{1}{8}$ cu. ft. of *dry* sand *A* : $4\frac{1}{3}$ cu. ft. of gravel *C*.

This and the nine preceding examples amply illustrate how the gradings of various mixes of two aggregates are calculated and compared with type gradings. Knowledge of the effects of departures from the type gradings (Chapter VIII) enables one to deduce the probable qualities of the concrete. Deductions should be checked by making a trial mix. In making the trial mix one should measure carefully the weights and volumes of the sand and coarse aggregate, the weight of the water used, and the volume and weight of the batch of concrete. From the weight of cement used and the volume of concrete produced the cement content of the concrete can be calculated. The volume and weight of the batch give the weight per cubic foot of the fresh concrete.

Equipment.—Aggregates from small jobs should be sent to a laboratory for testing. On the job all that is necessary is a $\frac{1}{2}$-cu. ft. bucket, as described, and a means of weighing up to 100 lb., so that the weight per cubic foot of the concrete can be checked frequently. A slump cone may be used to keep the consistency constant, once it has been established. So long as the weight per cubic foot remains high enough and the concrete is sufficiently workable to give good surfaces there cannot be much wrong. Excess of sand or water would cause the weight per cubic foot to drop below the limit allowed. Insufficiency of sand or water would be quickly detected by the concrete becoming harsh and difficult to finish.

A slump cone is useful for maintaining a nearly constant consistency while

using the same aggregates, especially if the water content of the aggregates varies from day to day. It is not reliable when different aggregates are being used, because the same slump may then be obtained with very different proportions of water to cement, and, conversely, different slumps may be obtained with the same proportion of water to cement. This is well illustrated by *Fig.* 25, which is reproduced by permission of the Controller of H.M. Stationery Office, from the paper by W. H. Glanville (of the Road Research Laboratory, Department of Scientific and Industrial Research) on " The Effect of the Grading of the Aggregate on the Strength and Workability of Concrete," published in the Journal of the Institution of Municipal and County Engineers, July, 1937.

On bigger jobs a set of sieves is helpful, as it enables aggregates to be tested regularly on the site and proportions to be adjusted. For such works purposes Nos. 14 and 52 may be omitted from the set. On important large works a full set of sieves and a mechanical shaker should be installed.

When proportioning is by volume a " sand tester " should be used to determine the proper increase in the volume of damp sand to be used in order to allow for the effect of bulking.

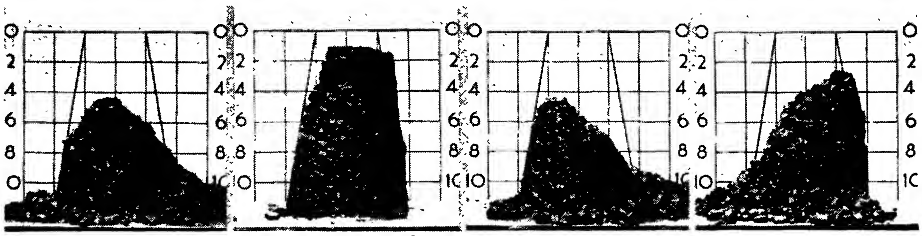


Fig. 28.—Variation in Slump with the same Water Content. Each sample is a 1 : 2 : 4 Mix with a Water-Cement-Ratio of 0·62.
(*Crown Copyright reserved.*)

In casting cubes for strength tests wooden moulds should never be used. The wooden sides warp slightly with the result that the faces of the cubes are never plane surfaces, but concave or convex. Even with the greatest care in the laboratory it is difficult to get reliable results with cubes cast in wooden moulds. The moulds should be steel or cast iron with machined surfaces.

Unless special methods of compacting are specified, cubes should be compacted by the methods used in placing the concrete on the works. If the concrete is merely rodded or spaded the cubes should be rodded. If the concrete is tamped the cubes should be tamped. If the concrete is vibrated the cubes should be vibrated.

Cubes should be matured in damp sand or damp saw-dust, and packed in damp sand or damp saw-dust when being sent to the laboratory. A 6-in. cube left in the open dries out very quickly—much faster than the mass of concrete it is supposed to represent. Too rapid drying reduces the strength at seven days by about one-third.

Checking Cement Content.—This can be done by checking the cement store and the mixer, and by weekly measurements of the concrete placed. More frequent checks can be made under favourable conditions by measuring the produce of a few hours' work and counting the number of bags used. On large

works it pays to have an assistant resident engineer whose main duty is to watch the concrete : to check proportions, time of mixing, consistency, ease of placing, and cement content.

Placing.—There are four principal methods of compacting concrete, (1) Pouring alone ; (2) Rodding, or spading ; (3) Tamping ; and (4) Vibration. Whichever is used the object is thorough compaction. Compaction is made easy by rendering the concrete fluid.

In No. 1 this is done by using excess water and sand and forming a thick liquid of cement, water, and fine sand in which the coarser sand particles and large aggregate are floated. This fluid fills the moulds and flows into every corner quite easily, but it contains far more water than is necessary for hydration, and as this dries out it leaves tiny voids which reduce the density of the concrete.

When rodding or spading is used it is not necessary to have the concrete so fluid and the proportion of water can be reduced. The rodding or spading makes the concrete temporarily fluid locally and enables it to be compacted readily.

Tamping when continued long enough converts relatively dry concrete into a jelly-like mass by forcing the aggregate particles close together and filling all the interstices with neat cement paste. When this jelly-like condition is reached the best compaction is attained. When heavy manual or mechanical tamping is to be used the concrete can be made very dry. Then, if the aggregates are properly graded and the tamping is well done, very strong and dense concrete is obtained. But this quality depends largely on the tampers ; slackness on their part results in voids and honeycombing, which mean weakness, permeability, and poor resistance to weathering.

High-frequency vibration rapidly reduces relatively dry concrete to a fluid condition, in which it not only compacts itself under its own weight and forces out air bubbles, but also tends to flow laterally. Moulds are well filled and good surfaces are obtained when vibration is properly used. The following precautions should be taken when concrete is placed by vibration:

(1) The shuttering should be strong, watertight, and airtight.

(2) The vibrators should have ample power.

(3) The concrete should be dumped in the shuttering at close intervals so that the energy of the vibrators is used solely for compacting and not for spreading as well.

(4) To get good surfaces use internal vibrators as close to the shuttering as possible without touching them.

(5) Use gradings agreeing with or slightly below the type gradings.

(6) Reduce the proportion of water well below that recommended on the diagrams as the upper limit for the appropriate type grading. Segregation occurs readily when wet concrete is vibrated. The real advantage of vibration is that it facilitates the placing of concrete having a low proportion of water to cement. Only relatively dry concrete should be used. Slumps should not exceed 1 in. with crushed stone aggregate and should not exceed 2 in. with gravel aggregates.

(7) As soon as the concrete becomes like a stiff jelly and air bubbles cease to break in the surface, vibration is completed. Over-vibration is liable to cause segregation and should be avoided.

(8) An experienced inspector should be employed to watch placing con-

stantly. Otherwise honeycombing may occur in some parts of the work and excess of mortar in others.

Inspection of Placing.—Careful inspection is advisable no matter what form of placing is used. The inspector's chief duties are to see that the concrete reaches its final position without undue delay and in good condition (not segregated), that it is not allowed excessive lateral travel in the shuttering, and, above all, that it is thoroughly compacted.

Construction Joints.—In horizontal joints excess water should be removed from the surface immediately after deposition of the concrete. Laitance on horizontal surfaces should be thoroughly scraped off and removed not later than twenty-four hours after placing the concrete. Before concreting is resumed the surfaces of construction joints should be thoroughly cleaned with wire brushes and water, and excess water should be drained off, leaving horizontal surfaces moist but free from standing water. Immediately before the next layer of concrete is placed neat cement grout should be brushed and worked into such surfaces, which should then be covered with a $\frac{1}{2}$-in. layer of 1 : 2 mortar. Special care should be taken to work and ram the mortar and fresh concrete upon and against the hardened concrete, and thoroughly to incorporate the $\frac{1}{2}$-in. layer of mortar with the freshly placed concrete.

Maturing.—The advantages of adequate moist maturing are not always appreciated. The disadvantages of too rapid drying out are too frequently ignored. Surface cracking (long cracks $\frac{1}{2}$ in. wide) are among the more disastrous and obvious effects of neglecting to keep exposed flat surfaces protected from a hot sun or a dry wind. Other defects may pass unnoticed for a time. One of these is the reduction of strength referred to already. Another is the formation of a skin of weak, porous, unhydrated concrete between $\frac{1}{16}$ in. and $\frac{1}{8}$ in. thick. Moist maturing is especially important in surfaces that are to be exposed to hard wear or severe weathering conditions and in water-retaining structures.

Exposed surfaces of concrete made with aluminous cement should be watered as soon as they are stiff enough to bear sprinkling. The heat generated during the early hours of hardening of aluminous cement concrete is great enough to dry out the surface, especially if the layer of concrete is 9 in. to 1 ft. thick, and constant watering is necessary during this critical period.

With regard to temperature it should be remembered that the rate of hardening at 40 deg. F. is about half that at 60 deg. F., and at lower temperatures the rate is still further retarded. This is apart altogether from the effects of allowing concrete to freeze at an early age. Normally the temperature of the concrete should be kept above 40 deg. F. and as far as possible between 50 deg. F. and 75 deg. F.

Acknowledgment.

Figs. 13 to 22 inclusive are copied, with small alterations, from diagrams in a paper read by the author before the Institution of Civil Engineers of Ireland and published in Vol. LXII of the Transactions of the Institution. The author is indebted to the Council of the Institution for permission to use these diagrams.

APPENDIX 1

PART OF BRITISH STANDARD SPECIFICATION, No. 812, 1938

METHOD 1: SIEVE ANALYSIS (GRADING).

Apparatus.

(*a*) Test sieves of the following sizes, conforming to B.S. 410, shall be used :

TABLE 1.—SERIES OF SIEVES RECOMMENDED FOR USE FOR THE SIEVE ANALYSIS OF ROAD MATERIALS.

Fine Mesh Wire Cloth	**200**, **100**, 72, **52**, 36, **25**, 18, **14**, 10, **7**
Medium Mesh Wire Cloth	**$\frac{1}{8}$ in., $\frac{3}{16}$ in.,** $\frac{1}{4}$ in., **$\frac{3}{8}$ in.**
Perforated Plate	**$\frac{1}{2}$ in., $\frac{3}{4}$ in.,** 1 in., **$1\frac{1}{2}$ in.,** 2 in., 3 in.

NOTE.—For practical purposes this series of sieves forms a $\sqrt{2}$ series, *i.e.*, the ratio of the sides of the openings of successive sieves approximate to $\sqrt{2}$.

For a complete sieve analysis all these sieves should be used, but for many purposes, *e.g.*, concrete aggregates, it is sufficient to use the sieves enumerated in heavy type.

The series in Table 1 has been recommended by a representative Committee of the Institution for adoption as the basic series of sieves from which all sieves required in the relevant British Standards should be chosen. Pending the revision of B.S. 598, " The Sampling and Examination of Bituminous Road Mixtures," the series specified in the 1936 edition is given in Table 2.

TABLE 2.—SIEVES FOR AGGREGATES FOR BITUMINOUS ROAD MIXTURES SPECIFIED IN B.S. 598—1936.

Fine Mesh Wire Cloth	200, 100, 85, 52, 36, 25, 18, 8.
Medium Mesh Wire Cloth	$\frac{1}{8}$ in., $\frac{3}{16}$ in., $\frac{1}{4}$ in., $\frac{3}{8}$ in.
Perforated Plate.	$\frac{1}{2}$ in., $\frac{3}{4}$ in., 1 in., $1\frac{1}{4}$ in., $1\frac{1}{2}$ in., $1\frac{3}{4}$ in., 2 in., $2\frac{1}{2}$ in.

Test Procedure.

(*a*) *Sample.*—The weight of sample for sieving shall be not less than the weight stated in Table 4. If the sample for sieving is obtained from a larger sample, care shall be taken to obtain a representative sample by quartering or otherwise.

(*b*) *Sieving.*—The sample after drying shall be passed successively through one of the series of sieves specified above. The order in which the sieves are used shall be stated in reporting the results. The sieving operation shall be conducted by imparting a lateral and vertical motion to the sieve, accompanied by jarring action, so as to keep the material moving continuously over the surface of the sieve. Material smaller than $\frac{3}{4}$ in. shall not be helped through the sieve.

Sieving shall be continued until not more than a trace of material passes the sieve in one minute when the sieve is shaken over a sheet of clean glazed paper.

NOTES.—(i) Sieving may be accelerated by occasionally clearing the mesh of the sieve of particles by means of a stiff brush operated against the under surface of the sieve.

(ii) " Balls " may be broken by the gentle pressure of the finger on them against the side of the sieve.

(iii) When the sample contains a wide range of sizes the analysis may be simplified by making a preliminary separation into two parts, fine and coarse, which are weighed. The fine portion may be reduced in bulk by quartering, the reduced portion weighed and passed through the specified finer sieves. When this is done, however, the total weight of the finer portion which is sieved shall not be less than the weight specified in Table 4 for the largest size of material present. From the results so obtained the proportion of each fraction present in the original sample shall be calculated.

(iv) When sieving material on sieves increasing progressively in size, the material shall first be passed over a 7 mesh B.S. test sieve to effect preliminary separation.

(*c*) *Weighing.*—The amount retained on each sieve shall be weighed on a balance or scale which is sensitive to at least 0·1 per cent. of the weight of the test sample.

Method of Reporting Results.

The percentage by weight retained on each sieve shall be calculated and the results shall be given to the nearest whole number. From these results, the cumulative percentage by weight of the total sample passing each of the sieves shall be calculated.

Appendixes 1 to 5 are reprinted by permission from British Standard Specification No. 812—1938, copies of which can be obtained from the British Standards Institution, 28, Victoria Street, London, S.W.1, price 3*s*. 8*d*. post free.

(*Author's Note.*)

Table 4 referred to here is not included in these extracts, but the relevant parts of it are given below.

PART OF TABLE 4.

Sizes of Samples for Sieve Analyses.

Material	Actual Size of Sample Tested
Sand.	500 g. (Approx. 1 lb.).
Aggregate up to	
$\frac{3}{8}$ in.	7 lb.
$\frac{3}{4}$ in.	28 lb.
$1\frac{1}{2}$ in.	112 lb.

The author's experience has been that samples as large as 28 lb. for $\frac{3}{4}$-in. aggregate, and 112 lb. for $1\frac{1}{2}$-in. aggregate are not necessary for the purposes dealt with in this book.

APPENDIX 2

PART OF BRITISH STANDARD SPECIFICATION, No. 812, 1938

MEASUREMENT OF AGGREGATE SHAPE (PERCENTAGE FLAKY AND ELONGATED MATERIAL).

Test Procedure.

(*a*) *Sample*.—When sieved on the sieves given in Table 1, Method 1, the sample to be tested shall contain a total of at least 200 particles of the two largest sizes present. If the sample is obtained from a larger sample, care shall be taken to obtain a representative sample by quartering or otherwise.

(*b*) *Sieving*.—The sample, after drying, shall be sieved in accordance with the method described in Method 1 on the sieves given in Table 1. In carrying out measurements of aggregate shape no account shall be taken of fine sizes of which less than 2 per cent. is present or which are not given in Table 3.

(*c*) *Separation of Flaky Material*.—After sieving as described in Clause (*b*), the material shall be gauged for thickness either individually on a metal gauge of the pattern shown in Fig. 1 or in bulk on sieves having elongated slots. The height of the opening or the width of the slots shall be the dimension specified in the second column of Table 3 for the appropriate size of material.

TABLE 3.—Dimensions of Thickness and Length Gauges.

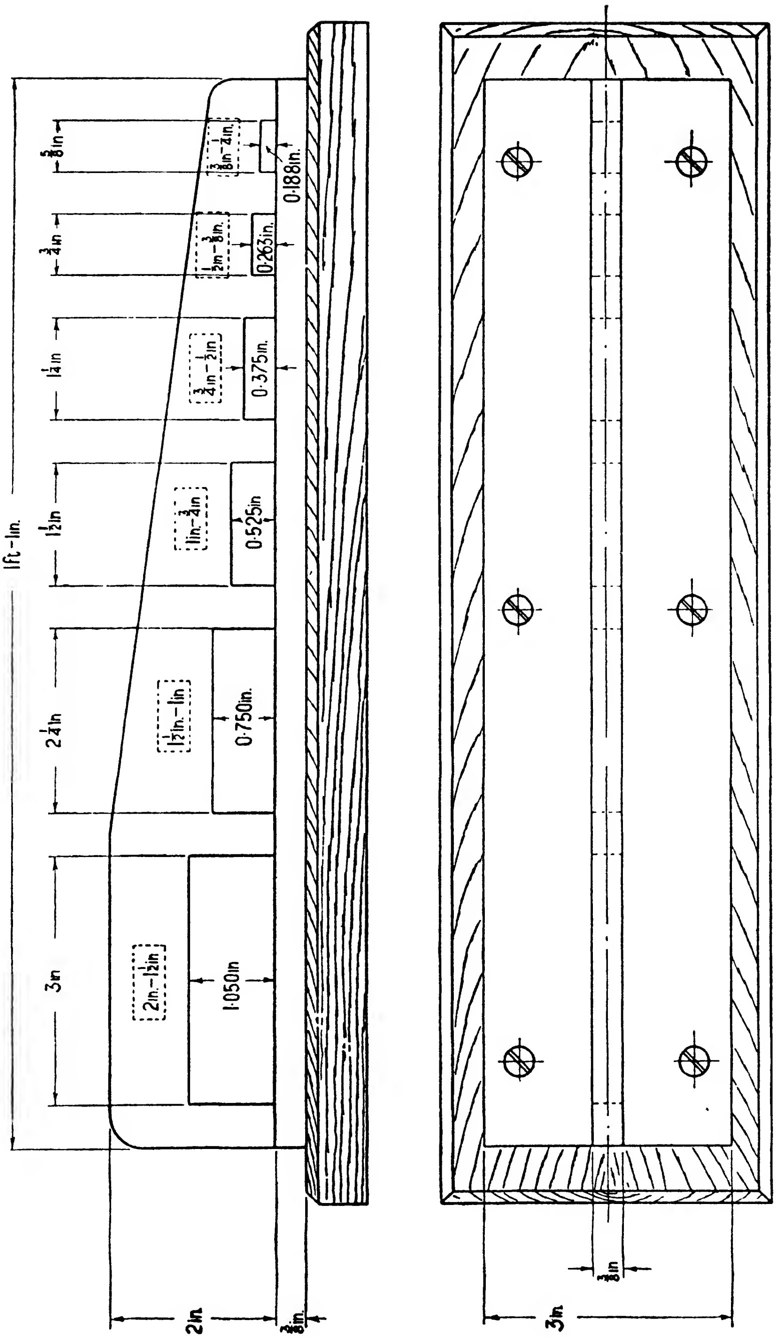
Size of aggregate	Gauge Thickness*	Gauge Length†
	in.	in.
Passing 2 in. retained 1½ in. B.S. Sieves .	1·050	3·15
,, 1½ in. ,, 1 in. ,, ,, .	0·750	2·25
,, 1 in. ,, ¾ in. ,, ,, .	0·525	1·57
,, ¾ in. ,, ½ in. ,, ,, .	0·375	1·12
,, ½ in. ,, ⅜ in. ,, ,, .	0·263	0·79
,, ⅜ in. ,, ¼ in. ,, ,, .	0·188	0·56

* This dimension is equal to 0·6 times the mean sieve size.
† This dimension is equal to 1·8 times the mean sieve size.

(*d*) *Weighing of Flaky Material*.—The total amount passing the thickness gauges shall be weighed on a balance or scale sensitive to at least 0·1 per cent. of the weight of the test sample.

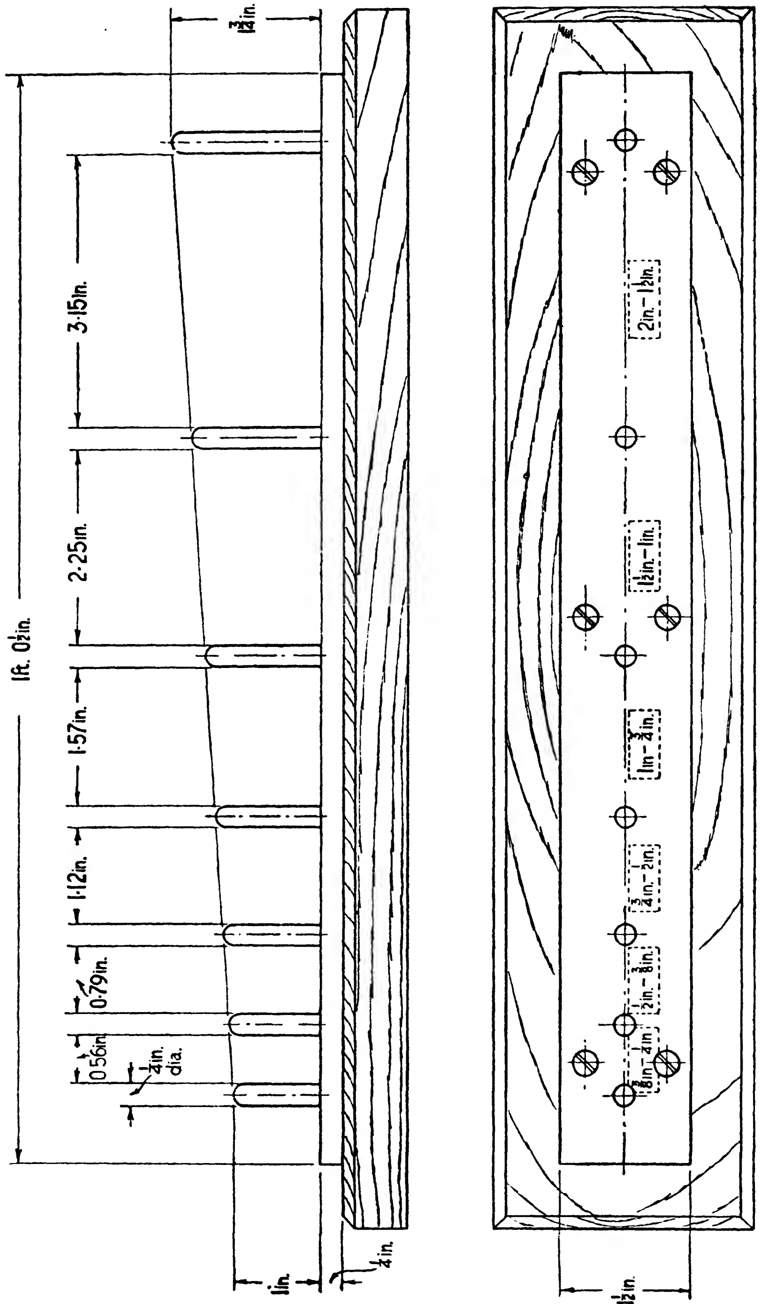
(*e*) *Separation of Elongated Material*.—After sieving as described in Clause (*b*) the material shall be gauged individually for length on a metal length gauge of the pattern shown in Fig. 2. The gauge lengths shall be those specified in the third column of Table 3 for the appropriate size of material.

(*f*) *Weighing of Elongated Material*.—The total amount retained by the length gauges shall be weighed on a balance or scale which is sensitive to at least 0·1 per cent. of the weight of the test sample.



NOTE.—Heights of gauge to be made to ± 0·002 in. Figures shown enclosed by dotted line to be stamped on.

Fig. 1.—Thickness Gauge.



NOTE.—Figures shown enclosed by dotted line to be stamped between studs.

Fig. 2.—Length Gauge.

Method of Reporting Results.

The percentage of flaky material present in a material is the total weight of the material passing the various thickness gauges expressed as a percentage of the total weight of the sample tested.

The percentage of elongated material is the total weight of the material retained on the various length gauges expressed as a percentage of the total weight of the sample tested.

APPENDIX 3

PART OF BRITISH STANDARD SPECIFICATION, No. 812, 1938

SAMPLING OF GRAVEL AND SAND.

Sampling before Delivery.

Whenever practicable, samples of gravel and sand shall be taken at the time of loading from the bins or storage piles. The gravel and sand shall be sampled as separate units and despatched to the testing laboratory as such.

When it is not practicable to take samples at the time of loading, and it is accordingly necessary to take the samples from the bins or storage piles, the following procedure is recommended :

Approximately equal samples shall be taken from different parts of the stock pile, care being taken to avoid sampling a segregated area of coarse-grained material which is likely to exist at the base of the pile. In sampling from a bin separate samples shall be taken from the top of the loading chute. At the latter place at least ½ cu. yard of material shall be run off and representative samples taken from it. These separate samples shall be well mixed to form a composite sample and the sample for test obtained by quartering, which is most accurately carried out with the material damp.

Sampling at Delivery.

Samples for both quality and size shall be taken from different parts of the vehicle or container during uploading. It is recommended that approximately equal samples be taken from the top, middle, and bottom of vehicle or container. These separate samples shall be well mixed to form a composite sample and the sample for test obtained by quartering, which is most accurately carried out with the material damp.

Sizes of Samples.

Samples of gravel up to and including 1 in. size shall contain at least 56 lb. of material.

Samples of sand shall contain at least 20 lb. of material.

Samples of " all in " sand and gravel shall contain at least 56 lb. of material.

APPENDIX 4

PART OF BRITISH STANDARD SPECIFICATION, No. 812, 1938

TEST FOR ORGANIC IMPURITIES IN SAND.*

NOTE.—In certain cases when specially required this test may also be used for natural aggregates, gravels, etc.

This is an approximate method of estimating injurious amounts of organic compounds present in natural sands, which are to be used in cement mortar or concrete. The principal value of the test is to furnish a warning that further tests of the sand are necessary before they are approved for use.

A representative sample of sand, weighing about one pound, shall be obtained by quartering.

A 12-oz. graduated clear glass bottle shall be filled to the 4½ oz. mark with the sand to be tested. A 3 per cent. solution of sodium hydroxide in water shall be added until the volume of the sand and liquid indicated after shaking is 7 fluid ounces. The bottle shall be stoppered, shaken vigorously and then allowed to stand for 24 hours.

A freshly prepared standard colour solution may be prepared by adding 2·5 ml. of a 2 per cent. solution of tannic acid in 10 per cent. alcohol to 97·5 ml. of a 3 per cent. sodium hydroxide solution. This should then be placed in a 12-oz. bottle, stoppered, shaken vigorously, and allowed to stand for 24 hours.

After standing for 24 hours the colour of the clear liquid above the sand shall be compared with the colour of the standard colour solution prepared at the same time and in accordance with the method described above, or with glass or other suitable standard of a colour similar to that of the standard solution.

The presence of organic impurity shall be assessed by the extent to which the liquid above the sand is darker in colour than the standard solution.

* The method is similar to A.S.T.M. Method C 40–33.

(Author's Note.)

A sand should not be condemned merely because it gives a dark colour in this test. The dark colour indicates the presence of organic matter which may interfere more or less seriously with the hardening of the concrete, or may have no harmful effect. A comparative crushing strength test must then be made with two 1 to 3 mortars (by weight), one made with the sand under test and the other with standard Leighton Buzzard sand. The proportion of water should be the same in each, namely, 12½ per cent. by weight of the dry material (cement and sand). Cubes 3 in. in size should be made and may be crushed at three or four days. If the mortar made with the sand under test is as strong as the mortar made with the standard sand, the organic matter is harmless. Some lake and river sands give a dark colour in the test for organic impurities and yet make mortar as strong as that made with the same proportion of a clean sand of similar grading.

APPENDIX 5

PART OF BRITISH STANDARD SPECIFICATION, No. 812, 1938

METHOD 17 : DETERMINATION OF AMOUNT OF MATERIAL FINER THAN 200 MESH B.S. TEST SIEVE IN AGGREGATES.*

Standard Method.

(*a*) *Scope.*—This method of test outlines the procedure for determining the total quantity of material in aggregates finer than a 200 mesh B.S. test sieve.

(*b*) *Apparatus.*—The apparatus shall consist of the following :

Sieves.—Two sieves, a 200 mesh B.S. test sieve, and a 14 mesh B.S. test sieve.

Container.—A pan or vessel of a size sufficient to contain the sample covered with water and to permit of vigorous agitation without inadvertent loss of any part of the sample or water.

(*c*) *Test Sample.*—The test sample shall be selected from material which has been thoroughly mixed and which contains sufficient moisture to prevent segregation. A representative sample, sufficient to yield not less than the appropriate weight of dried material, as shown in Table 6, shall be selected :

TABLE 6.—SIZE OF SAMPLE.

Nominal size of largest particle	Approximate minimum weight of sample
in.	Kg.
$\frac{1}{4}$	0·5
$\frac{3}{4}$	2·5
$1\frac{1}{2}$ or over	5·0

(*d*) *Procedure.*—The test sample shall be dried to constant weight at a temperature between 100° C. and 110° C. (212° F. and 230° F.) and weighed. (Weight A.)

The test sample after being dried and weighed shall be placed in the container and sufficient water added to cover it. The contents of the container shall be agitated vigorously and the wash water poured immediately over the sieves, arranged with the coarser sieve on top.

The agitation should be sufficiently vigorous to result in the complete separation from the coarse particles of all particles finer than the 200 mesh B.S. test sieve and bring the fine material into suspension in order that it will be removed by decantation of the wash water. Care shall be taken to avoid, as much as possible, decantation of the coarse particles of the sample. The operation shall be repeated until the wash water is clear.

All material retained on the sieves shall be returned to the washed sample. The washed aggregate shall be dried to constant weight at a temperature between 100° C. and 110° C. (212° F. and 230° F.) and weighed. (Weight B.)

(*e*) *Calculation of Results.*—The results shall be calculated from the following formula :

$$\left.\begin{array}{r}\text{Percentage of material finer}\\ \text{than 200 mesh B.S. test sieve}\end{array}\right\} = \frac{A - B}{A} \times 100$$

* The method is similar to A.S.T.M. Method C 117–37.

(*f*) *Check Determinations.*—When check determinations are desired, the wash water shall be either evaporated to dryness or filtered through tared filter paper which shall subsequently be dried, and the residue weighed. (Weight C.) The percentage shall be calculated from the following formula :

$$\left.\begin{array}{r}\text{Percentage of material finer}\\ \text{than 200 mesh B.S. test sieve}\end{array}\right\} = \frac{C}{A} \times 100.$$

Preliminary Field Decantation Test.

This method of test is intended as a guide to the quantity of silt, loam, clay, etc.

A sample of the sand to be tested shall be placed in a 200 ml. B.S. measuring cylinder filling it up to the 100 ml. mark.

Clean water shall be added up to the 150 ml. mark.

The mixture shall be shaken vigorously and the contents allowed to settle for one hour.

The volume of silt visible at the surface of the sand shall be noted and recorded as the percentage volume of silt in the sand.

APPENDIX 6

STANDARD METHOD OF TEST FOR CONSISTENCY OF CONCRETE (SLUMP TEST)

The test is to be used both in the laboratory and during the progress of the work for determining the consistency of concrete.

The test specimen shall be formed in a mould in the form of the frustum of a cone with internal dimensions as follows : Bottom diameter, 8 inches ; top diameter, 4 inches, and height 12 inches. The bottom and the top shall be open, parallel to each other, and at right angles to the axis of the cone. The mould shall be provided with suitable foot pieces and handles. The internal surface shall be smooth.

Care shall be taken to ensure that a representative sample is taken.

The internal surface of the mould shall be thoroughly clean, dry, and free from set cement before commencing the test.

The mould shall be placed on a smooth, flat, non-absorbent surface, and the operator shall hold the mould firmly in place, while it is being filled, by standing on the foot pieces. The mould shall be filled to about one-fourth of its height with the concrete which shall then be puddled, using 25 strokes of a $\frac{5}{8}$-inch rod, 2 feet long, bullet pointed at the lower end. The filling shall be completed in successive layers similar to the first and the top struck off so that the mould is exactly filled. The mould shall then be removed by raising vertically, immediately after filling. The moulded concrete shall then be allowed to subside and the height of the specimen measured after coming to rest.

The consistency shall be recorded in terms of inches of subsidence of the specimen during the test, which shall be known as the slump.

APPENDIX 7

STANDARD METHOD OF MAKING WORKS CUBE TESTS OF CONCRETE

The method described applies to compression tests of concrete sampled during the progress of the work.

Size of Test Cubes and Moulds.—The test specimens shall be 6-inch cubes. The moulds shall be of steel or cast iron, with inner faces accurately machined in order that opposite sides of the specimen shall be plane and parallel. Each mould shall be provided with a base plate having a plane surface and of such dimensions as to support the mould during filling without leakage and preferably attached by springs or screws to the mould. Before placing the concrete in the mould both the base plate and the mould shall be oiled to prevent sticking of the concrete.

Sampling of Concrete.—Wherever practicable concrete for the test cubes shall be taken immediately after it has been deposited in the work. Where this is impracticable samples shall be taken as the concrete is being delivered at the point of deposit, care being taken to obtain a representative sample. All the concrete for each sample shall be taken from one place. A sufficient number of samples, each large enough to make one test cube, shall be taken at different points so that the test cubes made from them will be representative of the concrete placed in that portion of the structure selected for tests. The location from which each sample is taken shall be noted clearly for future reference.

In securing samples the concrete shall be taken from the mass by a shovel or similar implement and placed in a large pail or other receptacle, for transporting to the place of moulding. Care shall be taken to see that each test cube represents the total mixture of concrete from a given place. Different samples shall not be mixed together, but each sample shall make one cube. The receptacle containing the concrete shall be taken to the place where the cube is to be moulded as quickly as possible and the concrete shall be slightly re-mixed before placing in the mould.

Consistency.—The consistency of each sample of concrete shall be measured, immediately after re-mixing, by the slump test made in accordance with the Method of Test for Consistency of Concrete given in Appendix 6.

Providing that care is taken to ensure that no water is lost the material used for the slump tests may be re-mixed with the remainder of the mix before making the test cube.

Compacting.—Concrete test cubes shall be moulded by placing the fresh concrete in the mould in three layers, each layer being rammed with a steel bar 15 inches long and having a ramming face of 1 inch square and a weight of 4 lb. For mixes of $1\frac{1}{2}$ inches slump, or less, 35 strokes of the bar shall be given for each layer; for mixes of wetter consistency the number may be reduced to 15 strokes per layer.

Curing.—The test cubes shall be stored at the site of construction, at a place free from vibration, under damp sacks for 24 hours ($\pm \frac{1}{2}$ hour) after which time they shall be removed from their moulds, marked and buried in damp sand until the time for sending to the testing laboratory. They shall then be well packed in damp sand or other suitable damp material and sent to the testing laboratory, where they shall be similarly stored until the date of test. Test cubes shall be kept on the site for as long as practicable but at least three-fourths of the period before test except for tests at ages less than seven days.

The temperature of the place of storage on the site shall not be allowed to fall below 40° F., nor shall the cubes themselves be artificially heated.

Record of Temperatures.—A record of the maximum and minimum day and night

temperatures at the place of storage of the cubes shall be kept during the period the cubes remain on the site.

Method of Testing.—All compression tests on concrete cubes shall be made between smooth plane steel plates without end packing, the rate of loading being kept approximately at 2000 lb. per square inch per minute. One compression plate of the machine shall be provided with a ball seating in the form of a portion of a sphere, the centre of which falls at the central point of the face of the plate.

All cubes shall be placed in the machine in such a manner that the load shall be applied to the sides of the cubes as cast.

(*Author's Note.*)

The utmost importance should be attached to securing a representative sample of the concrete and to placing it properly in the mould. The standard method of compacting should be followed only when that method resembles the method used on the works in placing the concrete in the forms. It would be a wrong method to use in sampling concrete from a road or other work in which the concrete is being tamped; in such a case the concrete should be tamped in the cube mould. Where concrete is being compacted by vibration the test cubes should also be compacted by vibration.

The slump test is not necessary unless it is being regularly used on the works.

It is of the utmost importance to follow the method of curing and packing in damp sand described here. If cubes are allowed to dry quickly or are packed in dry material at an early age the strength obtained may be only two-thirds or less of the strength obtained when the standard method is followed.

APPENDIX 8

INCREASE OF CRUSHING STRENGTH OF CONCRETE WITH AGE

The rate of increase of crushing strength of concrete with age depends upon the quality of the cement, curing conditions, temperature, and to some extent on the proportion of water to cement. It might be misleading to give definite strengths at different ages without quoting all the circumstances of the tests. The information contained in the following tables will be found useful for forecasting the strengths at other ages from strengths determined by test at 7 days or 3 days as the case may be.

The first table shows the relative strengths that may be expected at 3, 7, 28, and 90 days with concretes containing ordinary proportions of normal Portland cement and made and cured at about 60°. F. Strengths are expressed as percentages of the 7-day strength.

The second table shows strengths for similar concretes made with rapid-hardening Portland cement. In this case the relative strengths are given as percentages of the 3-day strength.

NORMAL PORTLAND CEMENT.

Crushing Strengths at 3, 7, 28, and 90 days at normal temperature expressed as percentages of the 7-day strength

Age in days	3	7	28	90
Usual values	60	100	163	212
Variations with quality of cement and proportions of water	48	100	141	160
	70	100	200	290

RAPID-HARDENING PORTLAND CEMENT.

Crushing strengths at 3, 7, and 28 days at normal temperatures expressed as percentages of the 3-day strength.

Age in days	3	7	28
Usual values	100	160	220
Variations with quality of cement and proportions of water	100	134	180
	100	190	280

The average 7-day strength of concrete made with normal Portland cement and about 6¾ gallons of water per 112 lb. of cement is about 2500 lb. per square inch, but this may vary between 2000 lb. and 3200 lb. per square inch according to the quality of the cement.

The average 3-day strength of concrete made with rapid-hardening Portland cement and about 6¾ gallons of water per 112 lb. of cement is about 2300 lb. per square inch, but this may vary between 1500 lb. and 3200 lb. per square inch.

It is notable that some of the highest quality "normal" Portland cements give higher strengths at 3 days or 7 days than some "rapid-hardening" Portland cements at the same age, other things being the same for both.

APPENDIX 9

GLOSSARY

ARBITRARY PROPORTIONS.—Proportions of cement to sand to coarse aggregate which have been found to give reasonably satisfactory results in certain districts. They are expressed as proportions by volume, and the volume of coarse aggregate is usually twice the volume of fine aggregate. The usual arbitrary proportions are $1 : 1 : 2$, $1 : 1\frac{1}{2} : 3$, $1 : 2 : 4$, $1 : 2\frac{1}{2} : 5$, $1 : 3 : 6$. These are conveniently described as $1 : n : 2n$.

BULKING (of Sand).—Increase of volume over volume of dry sand when the sand becomes *moist* but not saturated with water.

CEMENT CONTENT.—Weight of cement in finished volume of concrete, expressed in pounds of cement per cubic yard of concrete.

CEMENT-WATER-RATIO.—The ratio of the weight of cement to the weight of water in a batch of concrete.

CHECK MIX.—See Trial Mix.

COMBINED AGGREGATE.—The mixture of fine and coarse aggregates.

DENSITY OF CONCRETE.—The ratio of the sum of the volumes of solid particles in a mass of concrete to the volume occupied by the concrete. It is expressed as a decimal, thus 0·8. The weights and specific gravities of all the solid ingredients in a unit volume of concrete are necessary for determining density.

EQUIVALENT PROPORTIONS.—Proportions which produce the same weight of cement per cubic yard of finished concrete.

GAPPED GRADING.—Grading of an aggregate from which particles of one or more intermediate sizes are missing.

GRADING.—The relative proportions of particles of various sizes contained in an aggregate. It may be described (1) by stating the percentages by weight of the sample that are caught on each of a series of sieves, or (2) by stating the percentages by weight of the samples which are smaller than each of the sieve sizes. The latter method has been adopted by the British Standards Institution.

HONEYCOMBING.—Numerous voids big enough to be easily visible and apparent in surfaces from which forms have been removed.

INTERPOLATION (between Grading Curves).—Calculations of the position of a grading curve on the author's diagrams corresponding to proportions between either 4 and 5, 5 and 6, 6 and 8, or 8 and 10 cu. ft. of combined aggregate to 112 lb. of cement.

Example.—To find where the type curve for $6\frac{1}{4}$ cu. ft. of aggregate to 112 lb. of cement cuts the ordinate through the $\frac{3}{16}$-in. sieve size.

Type curve No. 6 cuts this ordinate at 42 per cent., and No. 8 cuts it at 47·5 per cent. The type curve for $6\frac{1}{4}$ cu. ft. cuts it at

$$42 \text{ per cent} + \frac{5\frac{1}{2} \times \frac{1}{4}}{2} \text{ per cent.}$$

$$= 42 + 0{\cdot}7$$
$$= 42{\cdot}7 \text{ per cent.}$$

SEMI-LOGARITHMIC PAPER.—Paper ruled in two directions at right angles with a natural scale (inches and tenths) in one direction and, in the other, a logarithmic scale on which distances are proportional to the logarithms of the numbers printed on the scale.

SIEVE ANALYSIS.—Separation of sample of aggregate into groups of particles of

graded sizes by means of a set of sieves, and determination of the percentage by weight of each group in the sample.

SLUMP.—Decrease in height of a frustum of a cone of fresh concrete when the conical mould is lifted vertically until clear of the concrete. The mould is 12 in. high, 8 in. in diameter at the base and 4 in. in diameter at the top. The fresh concrete is filled into the mould in a special manner.

SPECIFIC GRAVITY (of a solid).—The ratio $\dfrac{\text{Wt. of a given volume of the solid}}{\text{Wt. of an equal volume of water}}$.

TRIAL MIX (Trial Batch) (Check Mix).—A batch of concrete of previously determined proportions by weight made for the purpose of determining whether the workability, weight per cubic foot, cement content, and surface finish will be as anticipated.

TYPE GRADING.—Grading of a combined aggregate (containing particles of all sizes from maximum to minimum) of such a nature that concrete made with a specified number of cubic feet of that aggregate, 112 lb. of cement, and a specified proportion of water, will be both workable and dense.

VOIDS (in aggregates).—The spaces between the solid particles of an aggregate contained in a measuring vessel and between the aggregate particles and the walls of the vessel.

WATER-CEMENT-RATIO.—The ratio of the weight of water to the weight of cement in a batch of concrete.

WORKABILITY.—That quality of concrete which makes it easy to compact.

YIELD OF CONCRETE.—The volume of finished concrete relative to the amount of cement contained in it. (It may be expressed as cubic yards or cubic feet per 112-lb. bag of cement.)

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